GROWTH OF NOISINESS FOR TONES AND BANDS OF NOISE AT DIFFERENT FREQUENCIES
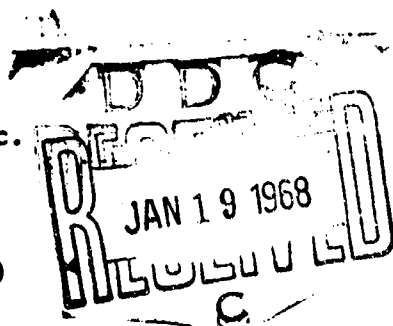
TECHNICAL REPORT

AD663904

December 1967

by

John E. Parnell
David C. Nagel
Hugh J. Parry

Bolt Beranek and Newman Inc.
15808 Wyandotte Street
Van Nuys, California 91406

Under Contract FA65WA-1180

JAN 19 1968

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Aircraft Development Service
Washington, D.C. 20590

88

TECHNICAL REPORT

DS-67-21

Contract No. FA65WA-1180

GROWTH OF NOISINESS FOR TONES AND BANDS
OF NOISE AT DIFFERENT FREQUENCIES

By

John E. Parnell
David C. Nagel
Hugh J. Parry

ABSTRACT

Judgment tests have been conducted to measure the growth
of noisiness for tones and narrow bands of noise under various
listening conditions. The growth of noisiness for a 1 kHz
tone and an octave band of noise centered at 1 kHz were measured
using both the method of adjustment and a magnitude estimation
method. Equal noisiness contours were determined for selected
listening conditions in order to measure the growth of noisi-
ness at frequencies other than 1 kHz. The growth of noisiness
was found to depend strongly on test method with the magnitude
estimation tests giving significantly larger values for
doubling or halving of perceived noisiness. Except for the
lowest reference level (50 dB SPL) the adjustment test results
ranged between 8.5 dB and 14.3 dB with a mean value of 11.5 dB.
At the 50 dB SPL reference level the mean value for doubling
the perceived noisiness is 16.7 dB. The magnitude estimation
tests yielded values between 20 dB and 27 dB for doubling of
noisiness depending on the reference number used by the test
subject. Equal noisiness contours are shown for pure tones
in a free field, one-third octave bands of noise in a free
field and one-third octave bands of noise in a diffuse field.
Also, comparisons of equal noise contours for one-second and
four-second stimulus durations and for loudness and noisiness
instructions are given. No significant differences were found
for these comparisons. Further, it was concluded that the
specific value used for the growth of noisiness did not
significantly affect the calculation of the relative PNL
values for many different spectra.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Concluded)

I. GENERAL INTRODUCTICN

Increasing interest in evaluating human response to environmental noise has emphasized the need for an accurate and reliable procedure for use in calculating the relative acceptability of different complex noise spectra. This requirement is particularly germane to the evaluation of vehicle noise and more specifically, aircraft noise. Noises of this type incorporate numerous parameters which influence subjective responses and each of these must be weighted in any predictive measure. The objective of such a calculation scheme has been one of incorporating all the salient factors influencing response to noise while at the same time maintaining a procedure simple enough for widespread application.

The current generation of calculation procedures concerned with predicting human response to noise are based exclusively on judged attributes such as loudness or noisiness. These procedures provide a useful and simple basis for the comparison of different noise spectra. Having used these techniques for several years, it is now evident that the original methods need to be refined and corrected for attributes such as duration, strong tone components and background noise. Also, certain original assumptions concerning this problem area need to be re-examined, specifically those concerning the growth of noisiness throughout the frequency spectrum and the shape of the equal noisiness contours for a range of sound pressure levels.

The current investigation has been directed toward one of the factors inherent in existing calculation procedures, i.e., the growth of noisiness as a function of sound pressure level throughout the frequency spectrum. This included a detailed study of the growth function at the reference frequency of 1 kHz as well as measurements of the growth of noisiness at other frequencies.

The report is divided into three main sections. The first two of these sections include complete descriptions of the separate phases of the investigation. The final section is a summary of the test results and the conclusions derived from the investigation.

II. GROWTH OF NOISINESS AT 1 kHz

A. Background

The increase in the noisiness attribute as sound intensity is increased is the so-called power law and is one of the factors comprising the scale of perceived noisiness. This power law, identical to the function used in the assessment of loudness, defines the change in the sound pressure level of a given sound required for a specific change, i.e., doubling or halving, of the subjective attribute.

In current practice, the growth of loudness (L) is described as a power function of intensity (I) where the judged loudness of a sound doubles with each 10 dB increase in the stimulus. This is an average of the data tabulated by Stevens (1955) and is based primarily on judgments of tones at 1000 Hz. This value of 10 dB for the intensity ratio corresponding to a loudness ratio of 2:1 gives an exponent of 0.3 for the power function ($\log_{10}2$) and loudness is then given by the expression

$$L = kI^{0.3}$$

In setting up a scale of loudness, an empirical relationship between loudness in sones and loudness level in phons (P) has been established. This relationship may be expressed as

$$P = 40 + 33.3 \text{ Log } L$$

and establishes that a change of 10 phons is equivalent to a factor of two in loudness. This relationship is used to determine the spacing between the equal loudness contours which in turn set the sone values used in the calculation of loudness for a complex noise. The homologous development of the scale of perceived noisiness has incorporated this 10 dB change in intensity per doubling of the subjective attribute as a basis for constructing the family of equal noisiness contours (Kryter, 1959). In this case the power law is used to specify the noy values (analogous to sones) associated with a wide range of sound pressure levels. This same power law was used in the subsequent modification of the equal noisiness contours and tabulated noy values (Kryter and Pearsons, 1963).

A comprehensive review of experimental methods and test results related to the growth of loudness has been published by Stevens (1955). This included a critical appraisal of several test methods and a tabulation of successive research data on decibel values required for doubling or halving of loudness for a range of sound pressure levels. The test methods reported included magnitude estimation, constant stimuli and adjustment, and for the most part the data approximate the 10 dB SPL per doubling/halving of loudness used in the calculation procedure.

Hellman and Zwislocki (1961) reported an investigation of the loudness function which in some ways paralleled the magnitude estimation tests from the present study. Their tests used the magnitude estimation method with a value of 10 assigned as a reference number at five different sensation levels. The results of these tests showed a steepening of the loudness function above the reference level. While there was some increase in the slope of the noisiness function above the 90 dB SPL reference in the current tests, the curves for the 70 dB SPL reference showed an opposite trend.

Since all previous investigations of this power law have been concerned with the attribute of loudness, one objective of the program described in this report was to make an independent and original determination of the power function for the attribute of noisiness. Further impetus for this investigation came from the results of magnitude estimation tests with aircraft flyover noise and sonic booms which yielded growth rates greater than 10 dB per doubling of noisiness (Bishop, 1966, Broadbent and Robinson, 1964). As an initial investigation into the growth of noisiness per se, a program was designed to map the growth of this noisiness attribute at 1 kHz for both a tone and an octave band of noise centered at this frequency.

In the course of analyzing the results of the growth of noisiness data, an interesting and perhaps significant observation was made. When computing the PNL of a complex noise, the noy tables are entered from the various band levels throughout the frequency spectrum. After summing the values according to the combination rule, the total noy value is specified in the 1000 Hz band and the equivalent perceived noisiness in decibel units is obtained. These two steps, entering and leaving the noy tables, are essentially an inverse process and do not appear to significantly influence the calculation of relative PNL's for many different spectra. As a result, any value might be used for the growth of noisiness with little or no effect on the computation of relative acceptability of different noise spectra. Calculations of the PNL for a variety of noise spectra have been

made using values of 3 dB, 5 dB, 10 dB, 20 dB and 30 dB per doubling of noisiness with no significant differences in the resulting values. A more complete discussion of the influence of the power law exponent on noisiness calculations is given in Appendix III.

B. Test Procedure

A block diagram of the test instrumentation is shown in Figs. 1A and 2A of Appendix I. The two different test stimuli were selected in order to assess the effect of bandwidth on the growth of noisiness. The octave bandwidth for the noise stimulus was selected in lieu of a one-third octave bandwidth so that one of the stimuli exceeded a single critical bandwidth at this frequency. As a further check on the factors affecting the growth of noisiness for these stimuli, two different test methods were employed. These two methods, both forms of paired-comparison tests, were the method of adjustment and a magnitude estimation technique.

The initial phase of the growth of noisiness tests used the adjustment method, described by Stevens (1955) as a special class of the method of ratio determination, to produce specified multiples or fractions of a standard stimulus. This method requires the subject to control the level of the comparison signal and set it to the required ratio relative to the standard.

The stimulus schedule for the adjustment tests is shown in Table I. This sequence of twenty comparisons was presented in a randomized order to each of 12 test subjects. The test subjects were college students ranging in age from 17 to 42 with an average age of 23 years. All subjects showed normal hearing on audiometric screening tests.

The detailed instructions for the adjustment tests are presented as Appendix IIA. The subject was asked to adjust the level of the comparison signal to some fraction or multiple of the noisiness of the standard sound. The specific fraction or multiple was displayed on a panel in front of the subject for each trial. The subject could switch to each of the four-second samples as often as he wished in making his judgment. The stimulus presentations were accompanied by indicator lights on the control bos appropriately identifying the standard and comparison sounds.

The magnitude estimation tests were conducted using recorded stimulus pairs played back as a continuous sequence. Using this test method, a standard or reference sound is presented to the subject and is assigned an arbitrary value,

-4-

e.g., 10 or 100. Then a comparison tone is presented and the subject assigns a related number to the comparison stimulus based on its noisiness relative to the standard.

Both the tone and noise stimuli were presented at two different levels for the standard, 70 and 90 dB SPL. The comparison stimuli were then presented at seven different levels for each standard, ranging from 50 to 110 dB SPL. The test sequence contained thirty stimulus pairs including both tone and noise at the two reference levels. These thirty stimulus pairs were recorded in six different randomized orders for use in the tests.

The magnitude estimation judgments were divided into three sections, each with a different value assigned to the standard. For the first test section, each subject was asked to assign a number of his own choosing, designated "subjects choice", to the standard sound. The remaining two sections used the numbers 10 and 100 as values for the standard. The "subjects choice" section of the test was presented first to each subject and the 10 and 100 sections were presented randomly so there was no consistent order.

The subjects task was to record on an answer sheet the number he elected to assign to the comparison stimulus based on the specified value for the standard. The stimulus durations were four seconds for both the standard and comparison with a one-second silent interval between the stimuli. A six-second period following the stimulus pair was provided for the magnitude estimation judgment. Detailed test instructions are given in Appendix IIB.

A total of twenty-seven subjects were included in the magnitude estimation tests. These were college students ranging in age from 17 to 42 with an average age of 21 years. All subjects had normal hearing.

C. Test Results

1) Adjustment Tests

The results of the adjustment tests for the tone and the noise are presented in Figs. 1 and 2 respectively. Each figure includes the fractions and multiples judged for each of the four reference levels. The data points are the mean values for twelve subjects. These results are also given in Table II in a form comparable to the loudness data tabulated by Stevens (1955).
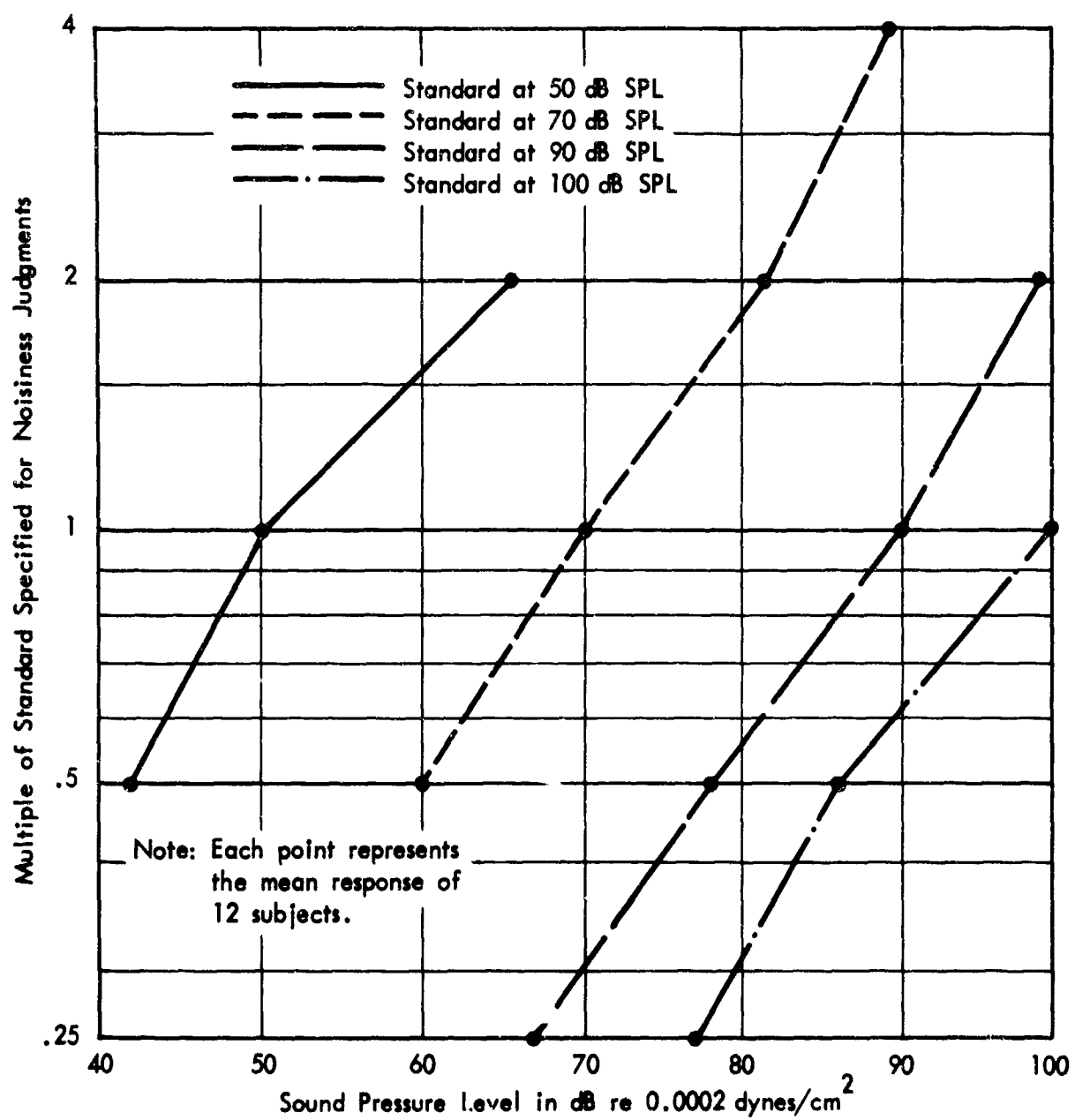
FIGURE 1.   GROWTH OF NOISINESS FOR A 1000 Hz TONE
USING METHOD OF ADJUSTMENT.
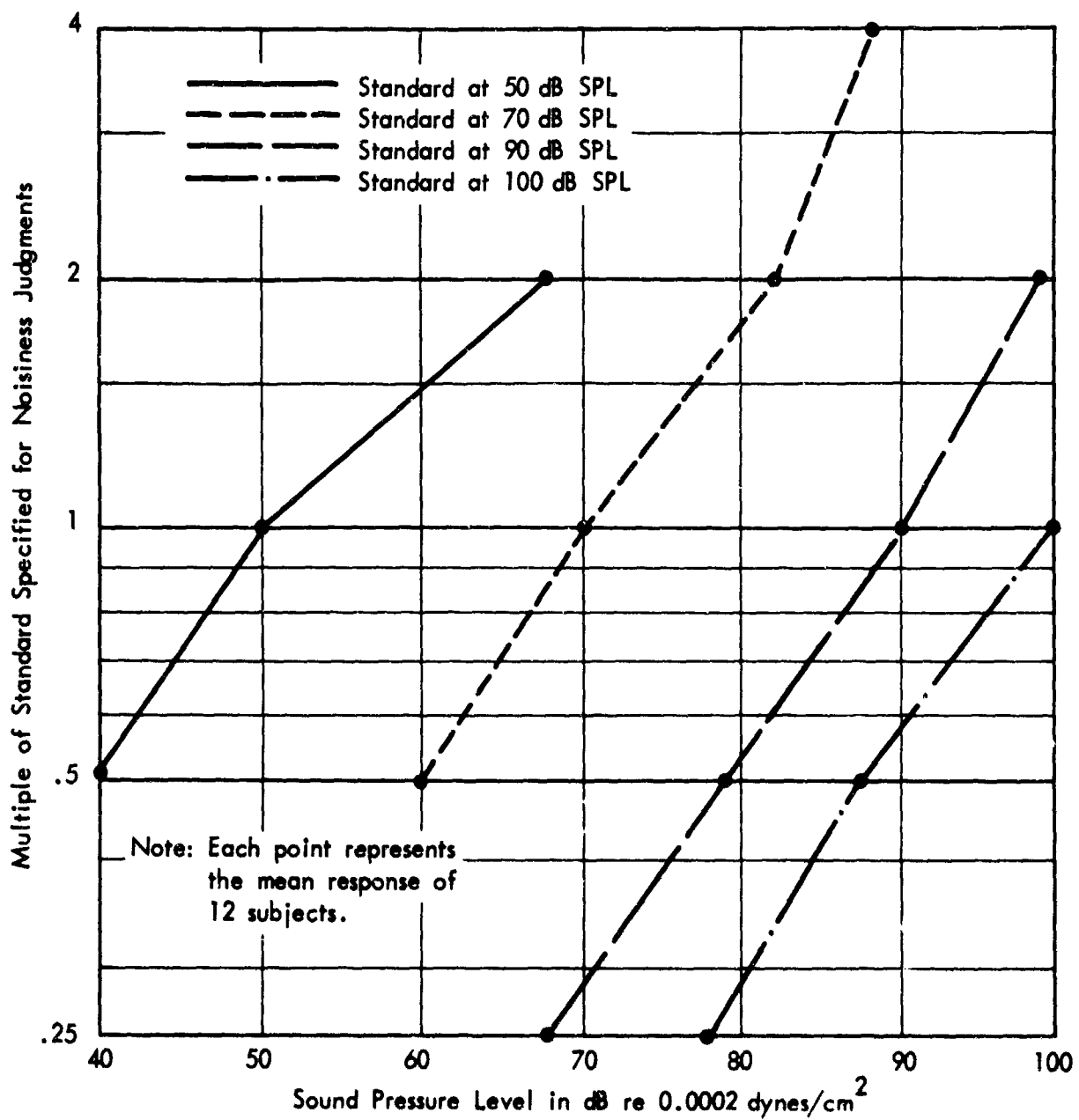
FIGURE 2.   GROWTH OF NOISINESS FOR A 1000 Hz OCTAVE
BAND OF NOISE USING METHOD OF ADJUSTMENT.

TABLE I

SCHEDULE USED FOR TEST I - METHOD OF ADJUSTMENT

Standard		Specified Multiple for Comparison Stimulus	
Noise*	Tone**		
100 dB	100 dB	1/2, 1/4	as noisy
90	90	2, 1/2, 1/4	as noisy
70	70	4, 2, 1/2	as noisy
50	50	2, 1/2	as noisy

*   Octave band of noise centered at 1000 Hz
** Pure tone at 1000 Hz

TABLE II

JUDGMENT RESULTS FOR GROWTH OF NOISINESS TESTS USING METHOD OF ADJUSTMENT

Specified Multiple	Stimulus	Comparison Level re Reference Level in dB Reference SPL			
		100	90	70	50
*1/4	O.B. Noise	-22.2	-22.5	--	--
1/2	O.B. Noise	-12.8	-11.6	-10.8	-11.1
2	O.B. Noise	--	+ 8.5	+12.0	+17.1
*4	O.B. Noise	--	--	+17.9	--
*1/4	1 kHz Tone	-22.6	-23.0	--	--
1/2	1 kHz Tone	-14.3	-12.0	- 9.5	- 8.8
2	1 kHz Tone	--	+ 9.1	+12.1	+16.3
*4	1 kHz Tone	--	--	+19.5	--

O.B. Noise: Octave Band of Noise Centered at 1 kHz.

* To obtain the values for doubling or halving the perceived noisiness cited in the text the multiples of 4 and 1/4 in the table were converted to noisiness ratios of 2:1 by taking half the decibel ratios corresponding to 4:1.

Except for the values for twice noisiness at a low
reference level (50 dB SPL), the results of the adjustment
tests ranged between 8.5 dB and 14.3 dB with a mean value
of 11.5 dB for doubling or halving the perceived noisiness
of the test stimuli. At the 50 dB SPL reference the average
increase for twice noisiness is 16.7 dB.

2) Magnitude Estimation Tests

The magnitude estimation judgments are shown in Figs. 3
through 8. Each figure gives both the mean and median values
for a specific standard, e.g., 10, 100 or "subjects choice",
at the two reference levels, 70 and 90 dB SPL. These values
were obtained by reducing the numbers assigned by the subjects
to the comparison stimuli to ratios. That is, if the value
for the standard was 10 and the subject called the comparison
23, a ratio of 2.3:1 was entered for that comparison.

The results of the magnitude estimation tests showed
consistently larger values for twice and half noisiness as
compared with the adjustment tests. These values ranged
from 20-27 dB increase for twice noisiness at the 70 dB SPL
reference and from 14-20 dB at the 90 dB SPL reference.

D. Discussion

1) Adjustment Tests

The data on the growth of noisiness obtained from the
adjustment tests in the current investigation are comparable
to the loudness values tabulated by Stevens (1955). Stevens
computed a median value of 10.0 dB for the 178 values of
decibel differences corresponding to a ratio of 2:1 for the
loudness of tones. Due to the skewness of the data, the
arithmetic mean of the numbers compiled by Stevens was 10.9
dB with a standard deviation of 3.9 dB. The current
noisiness data had a mean of 11.5 dB and a standard deviation
of 2.3 dB for 20 values (Table II). These averages are
quite similar and suggest that the subjects may have been
using the same attribute criteria in all the tests.

One other consistency between the data for the growth
of noisiness and those for loudness has been observed. At
lower sound pressure levels (50 dB), half noisiness requires
a smaller decibel change than twice noisiness. This is
reversed at higher sound pressure levels. This same
observation was made by Stevens (1955) for the loudness data.

2) Magnitude Estimation Tests

The results of the magnitude estimation judgments for the
growth of noisiness produced surprisingly shallow growth
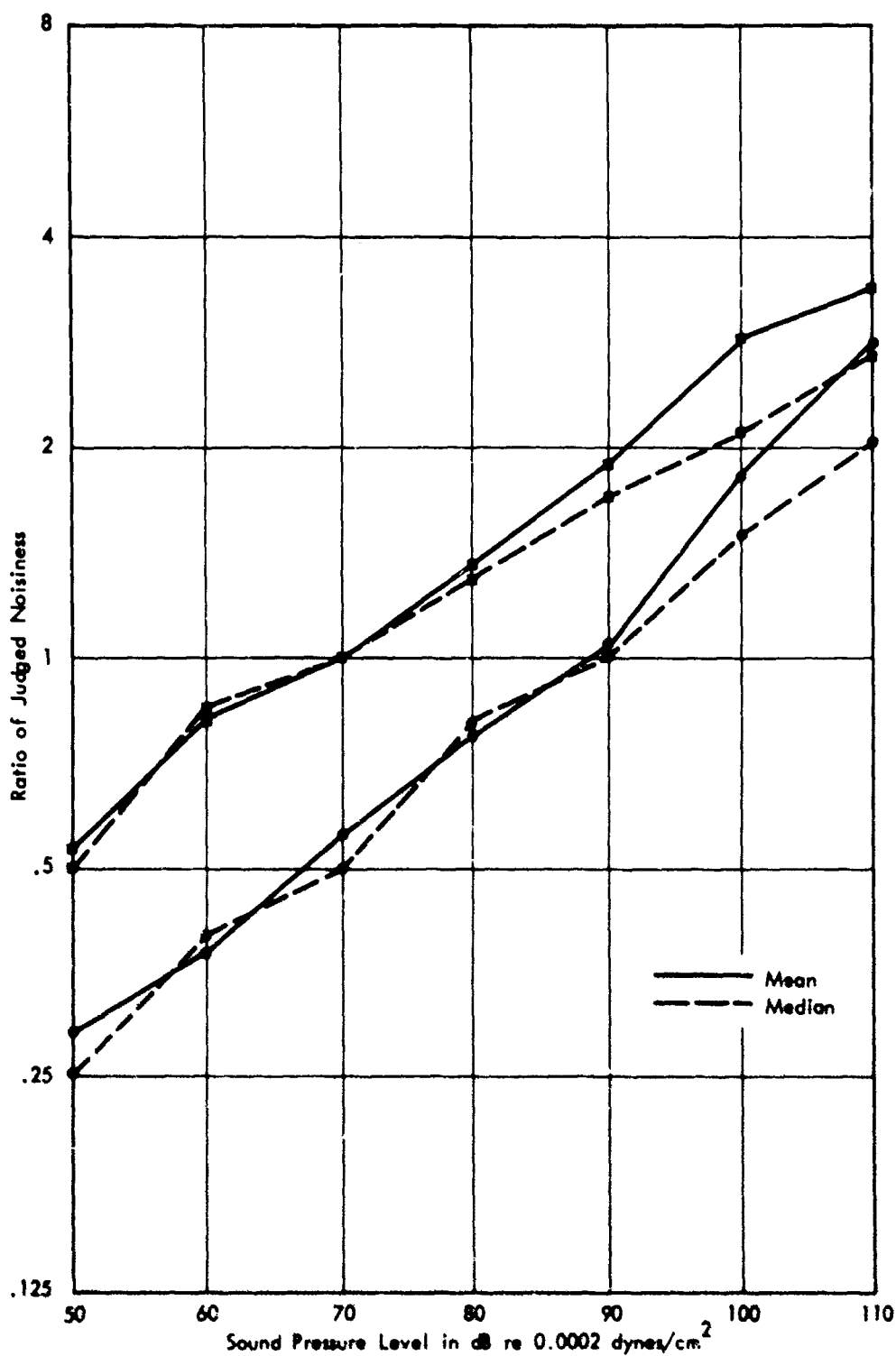
FIGURE 3. GROWTH OF NOISINESS FOR 1000 Hz TONE USING
METHOD OF MAGNITUDE ESTIMATION.
Standards at 70 and 90 dB SPL
Reference Number 10 Assigned to Standards

-10-
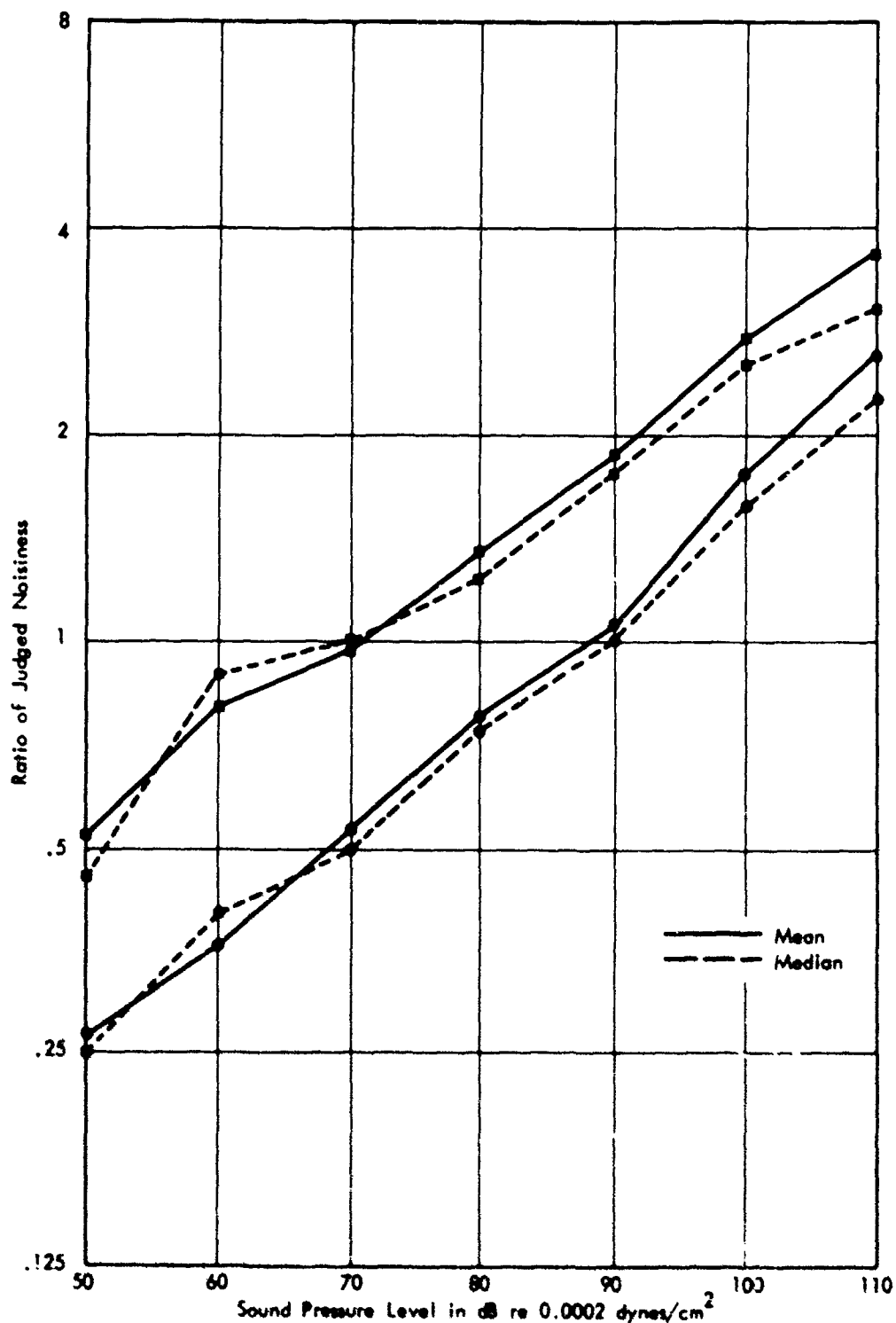
FIGURE 4. GROWTH OF NOISINESS FOR 1000 Hz TONE USING
METHOD OF MAGNITUDE ESTIMATION.
Standards at 70 and 90 dB SPL
Reference Number 100 Assigned to Standards
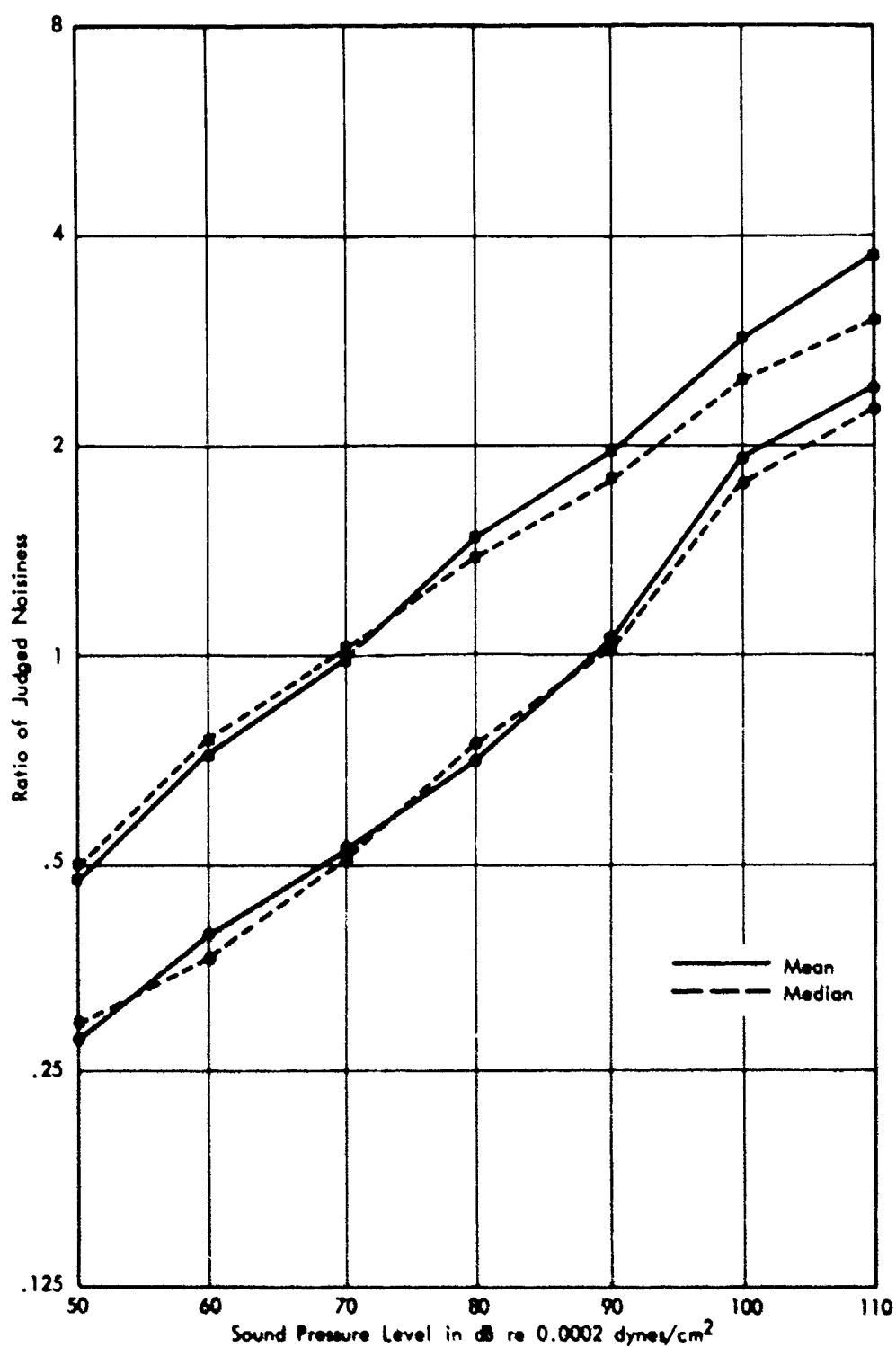
FIGURE 5. GROWTH OF NOISINESS FOR 1000 Hz TONE USING
METHOD OF MAGNITUDE ESTIMATION.
Standards at 70 and 90 dB SPL
Reference Number Chosen by Subject Assigned to Standards
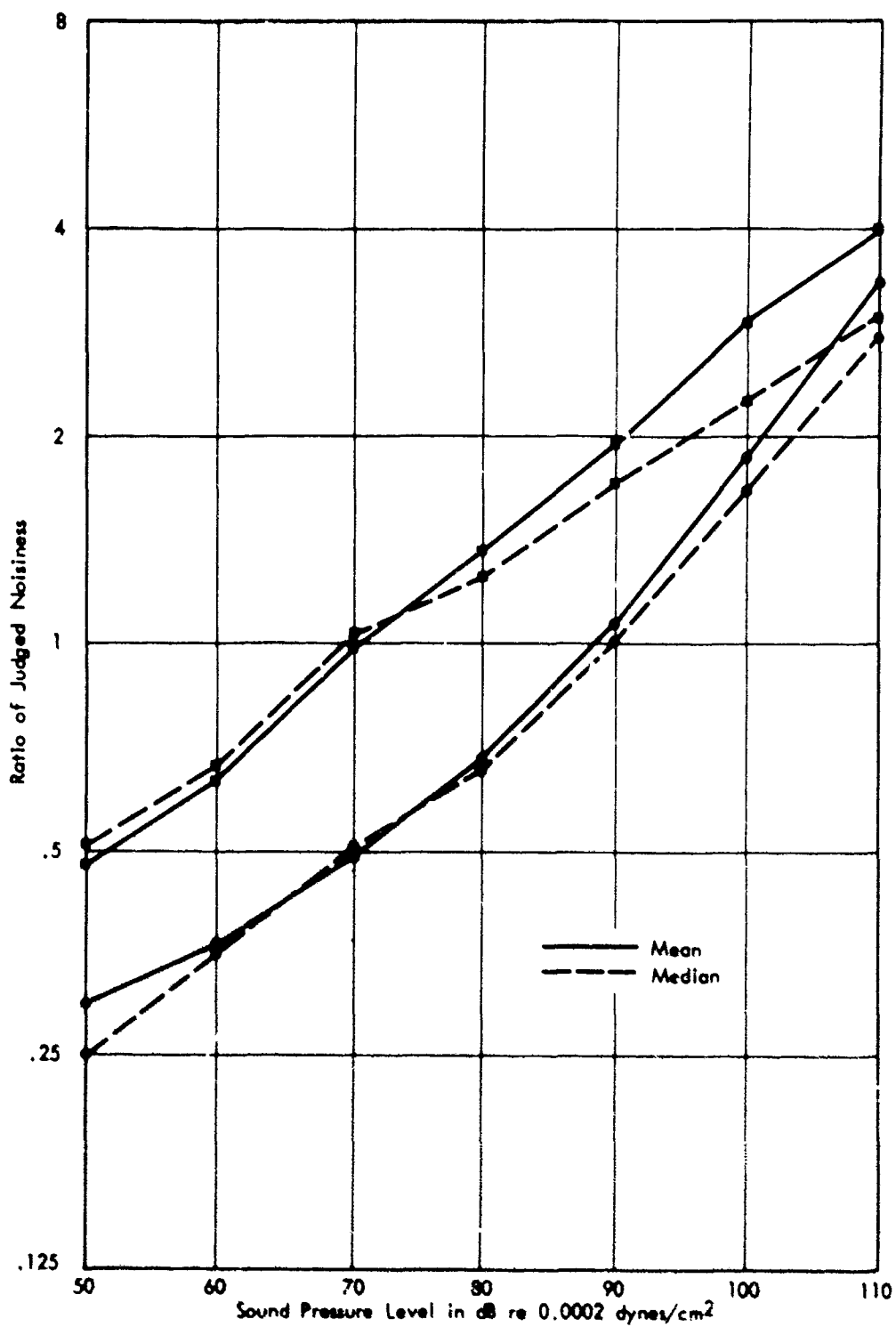
FIGURE 6. GROWTH OF NOISINESS FOR OCTAVE BAND OF NOISE
CENTERED AT 1000 Hz USING METHOD OF MAGNITUDE ESTIMATION
Standards at 70 and 90 dB SPL
Reference Number 10 Assigned to Standards

-13-
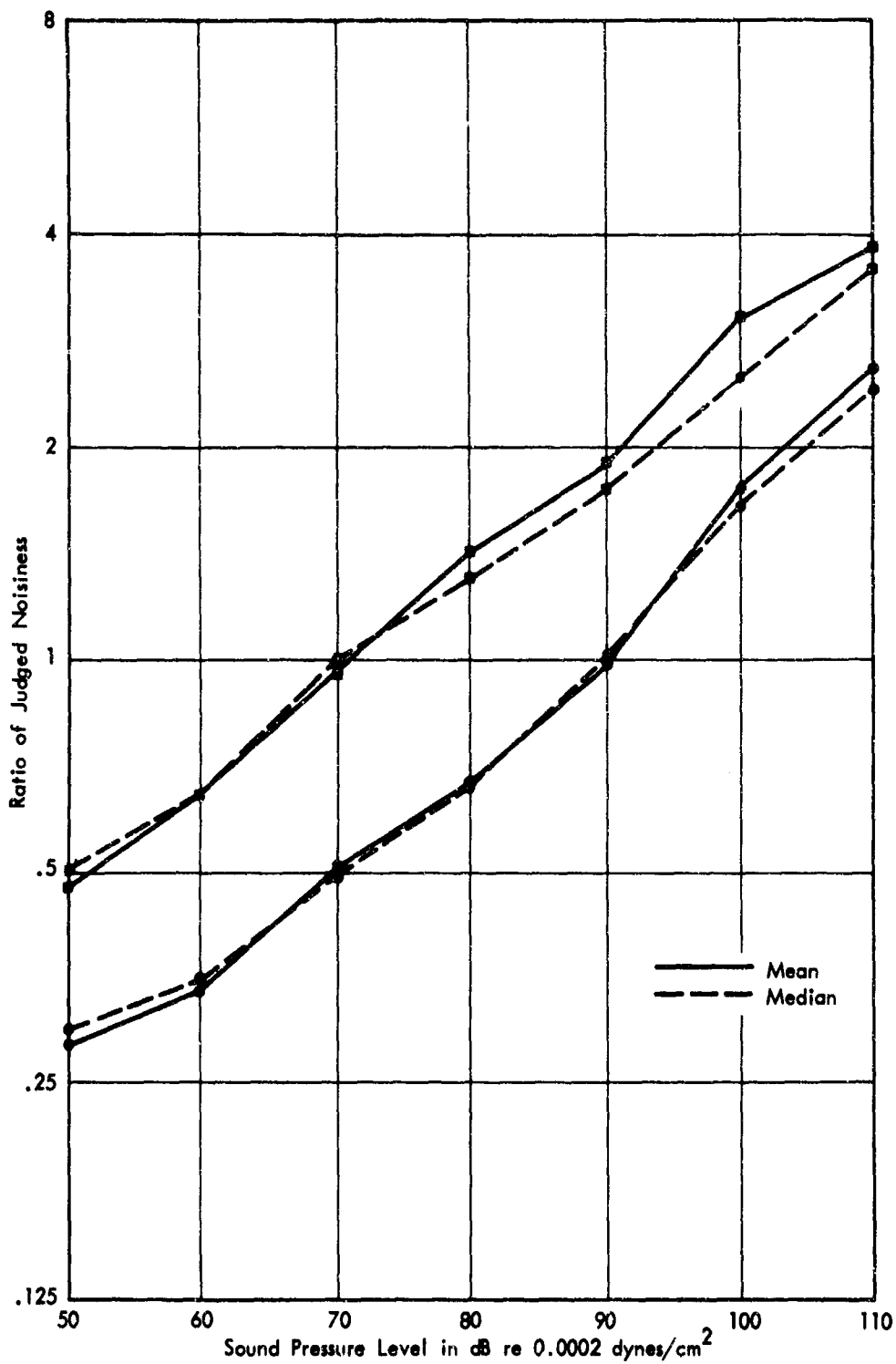
FIGURE 7. GROWTH OF NOISINESS FOR OCTAVE BAND OF NOISE
CENTERED AT 1000 Hz USING METHOD OF MAGNITUDE ESTIMATION
Standards at 70 and 90 dB SPL
Reference Number 100 Assigned to Standards

-14-
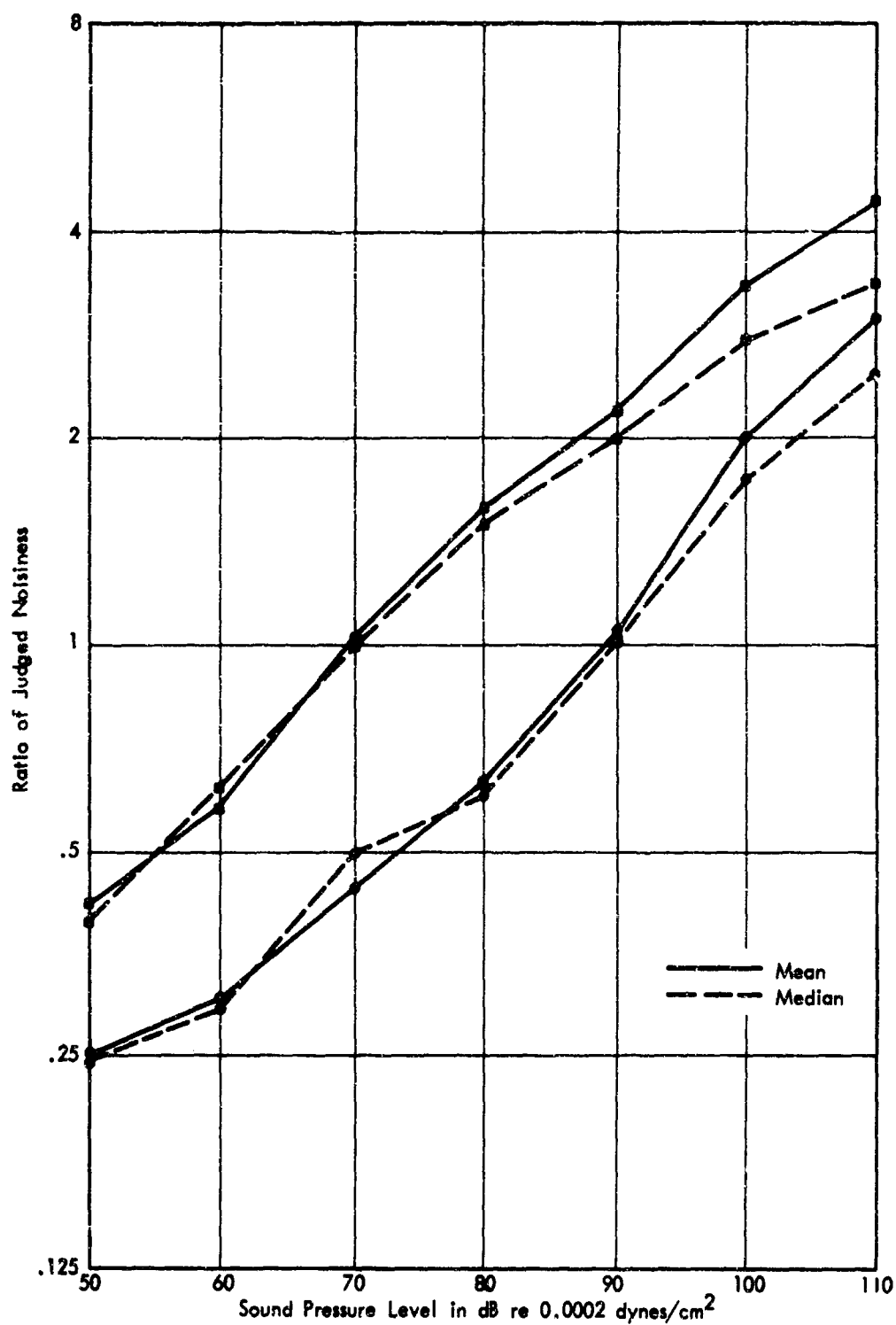
FIGURE 8. GROWTH OF NOISINESS FOR OCTAVE BAND OF NOISE
CENTERED AT 1000 Hz USING METHOD OF MAGNITUDE ESTIMATION
Standards at 70 and 90 dB SPL
Reference Number Chosen by Subject Assigned Standards

-15-

curves (Figs. 3 through 8). Reynolds and Stevens (1960)
observed that a change in the slope of the growth function
in this direction was a characteristic difference between
the methods of adjustment and magnitude estimation. However,
the differences in the noisiness tests were quite large,
with median values ranging up to 27 dB per doubling of
noisiness at a reference level of 70 dB SPL. The magnitude
estimation values for twice noisiness were consistently
greater than 20 dB for all reference values, i.e., 10, 100
and "subjects choice". No significant differences in the
growth of noisiness for the tone and the noise were observed.

III. GROWTH OF NOISINESS AT FREQUENCIES OTHER THAN 1 kHz

A. Background

As a second phase of the investigation of the scale of
perceived noisiness, the original test program was designed
to measure the noisiness function at two additional fre-
quencies, 250 Hz and 4 kHz. However, the results of the
growth of noisiness measurements at 1 kHz showed a strong
dependence on test method. Because of this variation, an
alternative approach to the problem was developed.

It is possible to measure the growth of noisiness through-
out the frequency spectrum by determining equal noisiness
contours at different reference levels. If this is done,
the contours should be parallel if the growth of noisiness
is the same at all frequencies. Any significant differences
in contour shape at different reference levels would be an
indication that the growth law is not constant at all
frequencies.

A program was therefore designed to measure equal
noisiness contours by equating both tones and noise bands
throughout the frequency spectrum with identical reference
stimuli at 1 kHz under a variety of listening conditions.
These contours, together with the growth of noisiness data
at 1 kHz would be used to map the growth function at
different frequencies.

In outlining this phase of the test program, the
following areas of investigation were established to include
some of the factors which might influence the shape of the
equal noisiness contours.

1) Determination of equal noisiness contours for <u>pure
    tones in a free-field environment</u> for a range of
    sound pressure levels.

2) Determination of equal noisiness contours for <u>one-
    third octave bandwidth noise in a free-field
    environment</u> for a range of sound pressure levels.

3) Determination of equal noisiness contours for <u>one-
    third octave bandwidth noise in a ᴜ.   .e field</u>
    environment for a range of sound pressure levels.

4) Comparison of equal noisiness contours using <u>one-
    second and four-second stimulus durations.</u> Existing
    equal sensation contours have been based on these

stimulus durations for loudness and noisiness respectively. Both were included in the current tests to provide an additional basis for comparing the results with existing data.

5) Determination of the effect of instructional set including a comparison of equal noisiness contours and equal loudness contours obtained under identical environmental conditions.

B. Test Procedure

The tests using pure tone stimuli were conducted in a free-field environment with frontally incident test signals. Subjects were tested singly while seated approximately five feet from the sound source. The adjustment method used in these tests required the subject to adjust the level of a comparison signal until it was judged to be equally as noisy as the standard or reference sound. The standard and comparison sounds were continuously alternating and the signal being presented was identified to the subject by indicator lights. The tests using bands of noise as stimuli followed the same procedure and were conducted in both the anechoic chamber and the semi-reverberant room. The test instructions used for the determination of equal noisiness contours are those presented in Appendix II-C, unless otherwise noted.

A stimulus duration of one second for both the standard and comparison sounds with a separation of one-half second between the stimuli was used for the pure tone tests. A 1 kHz tone was used as a standard signal. The comparison frequencies were 63, 125, 250, 500, 1k, 2k, 3.15k, 4k, 6.3k and 8kHz. The tests using one-third octave bandwidth noise stimuli included both one-second and four-second stimulus durations with a one-half second interval between stimuli. A one-third octave band of noise centered at 1 kHz was the standard signal for the noise tests.

C. Test Results

The results of the series of equal noisiness determinations will be described for each of the listening conditions. The basic results obtained for each different environment are presented along with the sequential development of averaged and smoothed equal noisiness contours.

1) Equal Noisiness Contours - Pure Tones in a Free-Field Environment

The test and re-test results for a group of twenty subjects are shown in Figs. 9 and 10. The five equal noisiness contours

-18-
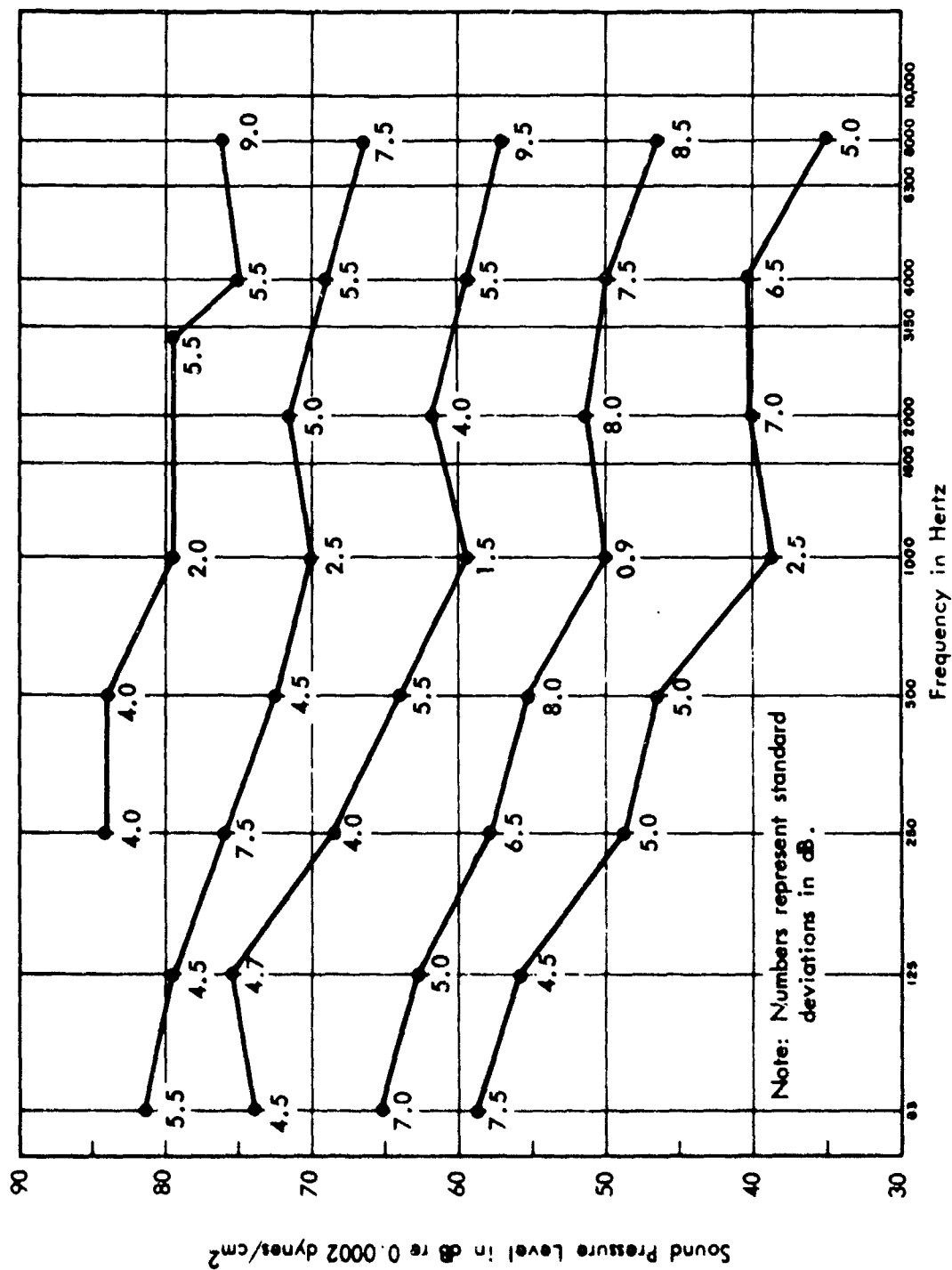
FIGURE 9. EQUAL NOISINESS CONTOURS FOR 1 SECOND, PURE TONE STIMULI TESTED IN THE ANECHOIC CHAMBER. BBN NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 20 SUBJECTS. SUBJECT GROUP I.

-19-
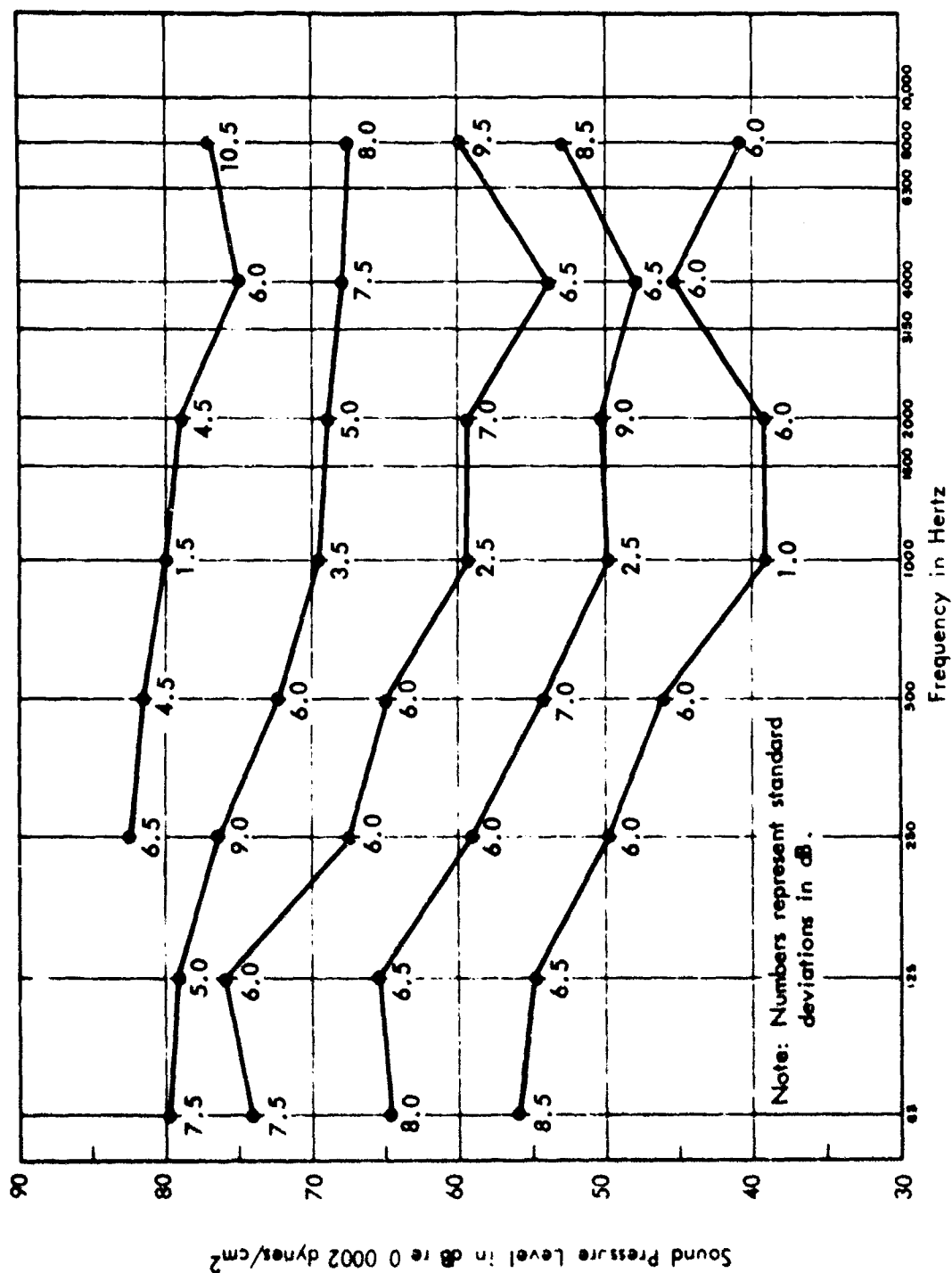
FIGURE 10. EQUAL NOISINESS CONTOURS FOR 1 SECOND, PURE TONE STIMULI TESTED IN THE ANECHOIC CHAMBER. BBN NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 20 SUBJECTS. SUBJECT GROUP I. (RETEST)

are presented at reference levels of 40,50,60,70 and 80 dB.
The median values for the twenty subjects are plotted in
Figs. 9 and 10 and these points are simply connected by
straight lines to form the initial contour shapes. The
value of one standard deviation in terms of number of
decibels at each point is shown numerically on both of
these figures.

An average of these same test and re-test values (Figs.
9 and 10) is shown in Fig. 11. The straight-line connections
of these averaged points were used as the basis for a family
of final smoothed contours.

The procedure used to develop a set of smoothed contours
is illustrated in Figs. 12 through 14. In Fig. 12, the
average contours from Fig. 11 have been normalized at 1 kHz
to show the changes as a function of sound pressure level
throughout the spectrum. This particular type of display
was then used to produce the visually smoothed contour
shown in Fig. 13. This curve smoothing process represents
an estimate of the true value of the test results, i.e.,
the shape and the contours would assume as the number of
test subjects and test frequencies increased. After the
smoothed contours were established in this fashion, they
were separated according to the sound pressure level of the
1 kHz standard used in the judgment tests. This produced
the final set of smoothed curves shown in Fig. 14. These
contours (Fig. 14) represent judgments of discrete frequency
stimuli from 63 Hz to 8 kHz matched to a 1 kHz standard by
the method of adjustment. These equal noisiness contours
are essentially parallel over a 40 dB range as shown in
Fig. 14. Relatively little compression of the contours was
evident at low frequencies so that, for these pure tone
stimuli, the growth of noisiness appears to be fairly con-
stant throughout the frequency spectrum.

  2) Equal Noisiness Contours - One-Third Octave Bandwidth
      Noise in a Free-Field Environment

The one-third octave bandwidth of pink noise was selected
as the stimulus for the remainder of the equal noisiness and
equal loudness determinations. This noise shape, when
compared with discrete frequencies, should provide some
initial information on the effects of bandwidth on noisiness
or loudness matching. In addition, this bandwidth of noise
approximates one critical bandwidth for frequencies above
100 Hz. This factor is of interest in assessing the effect
of masking in the calculation of the noisiness of complex
noises.
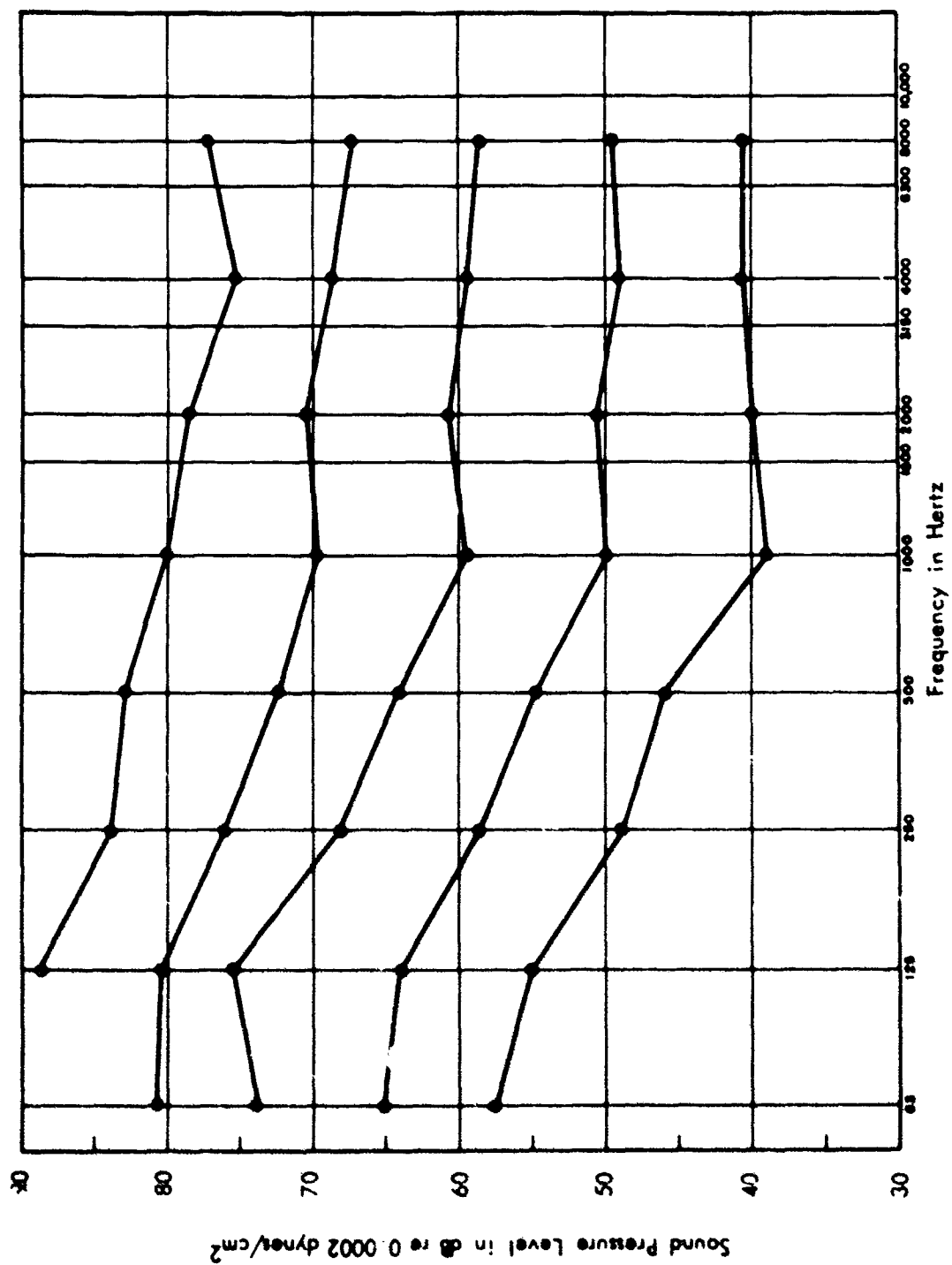
FIGURE 11. SUMMARY OF EQUAL NOISINESS DATA OBTAINED IN THE ANECHOIC CHAMBER FOR PURE TONE STIMULI. POINTS REPRESENT AN AVERAGE OF DATA FROM FIGURES 9 AND 10
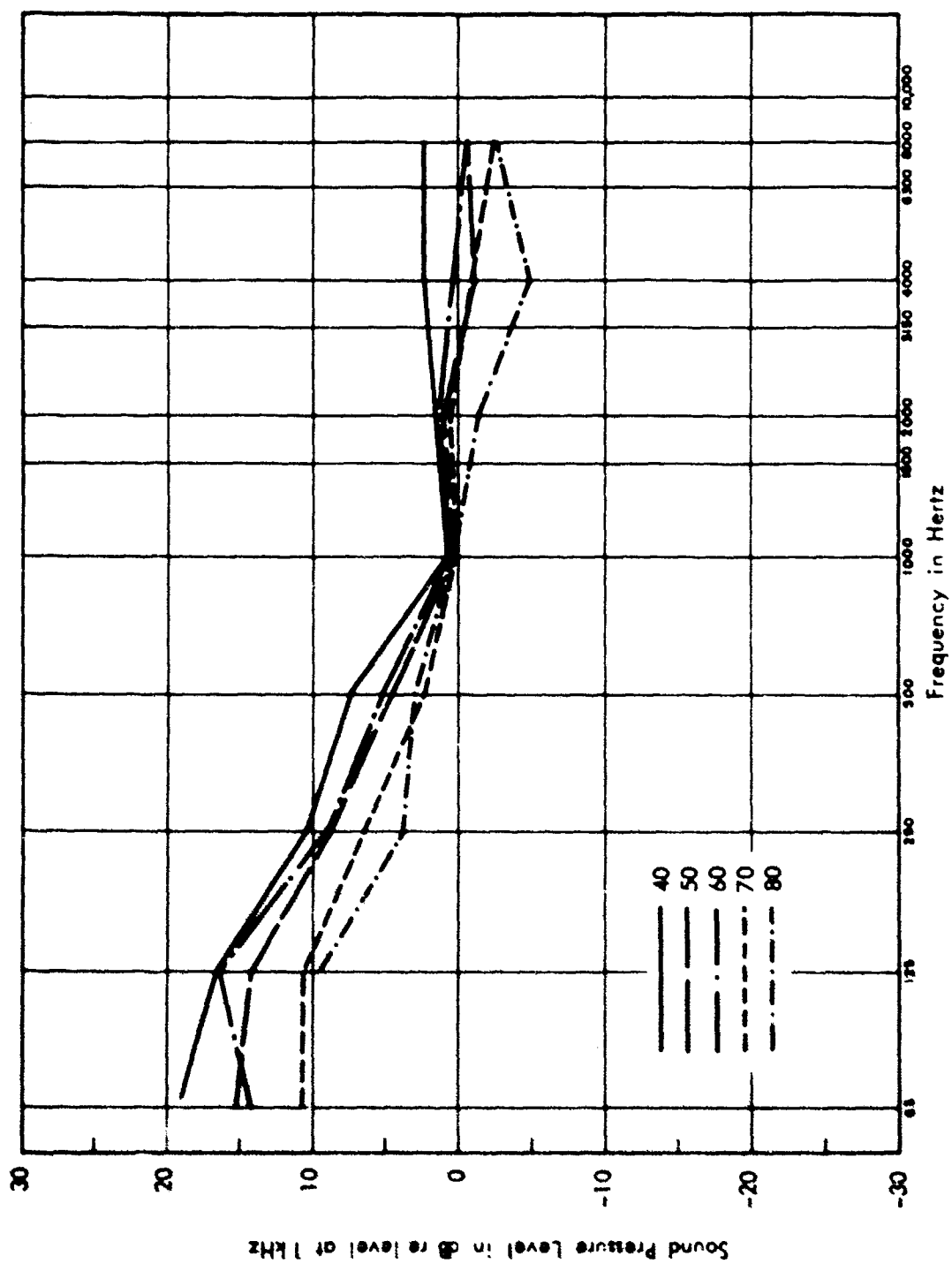
FIGURE 12. COMPARISON OF EQUAL NOISINESS CONTOURS OBTAINED FOR PURE TONE STIMULI AT 10 dB INTERVALS FROM 40 dB TO 80 dB SOUND PRESSURE LEVELS UNDER FREE FIELD (ANECHOIC CHAMBER) CONDITIONS. CURVES SHOWN ABOVE CONNECT ACTUAL DATA POINTS PRIOR TO SMOOTHING OF THE CONTOURS Numbers Represent Sound Pressure Level at 1kHz for a Particular Contour
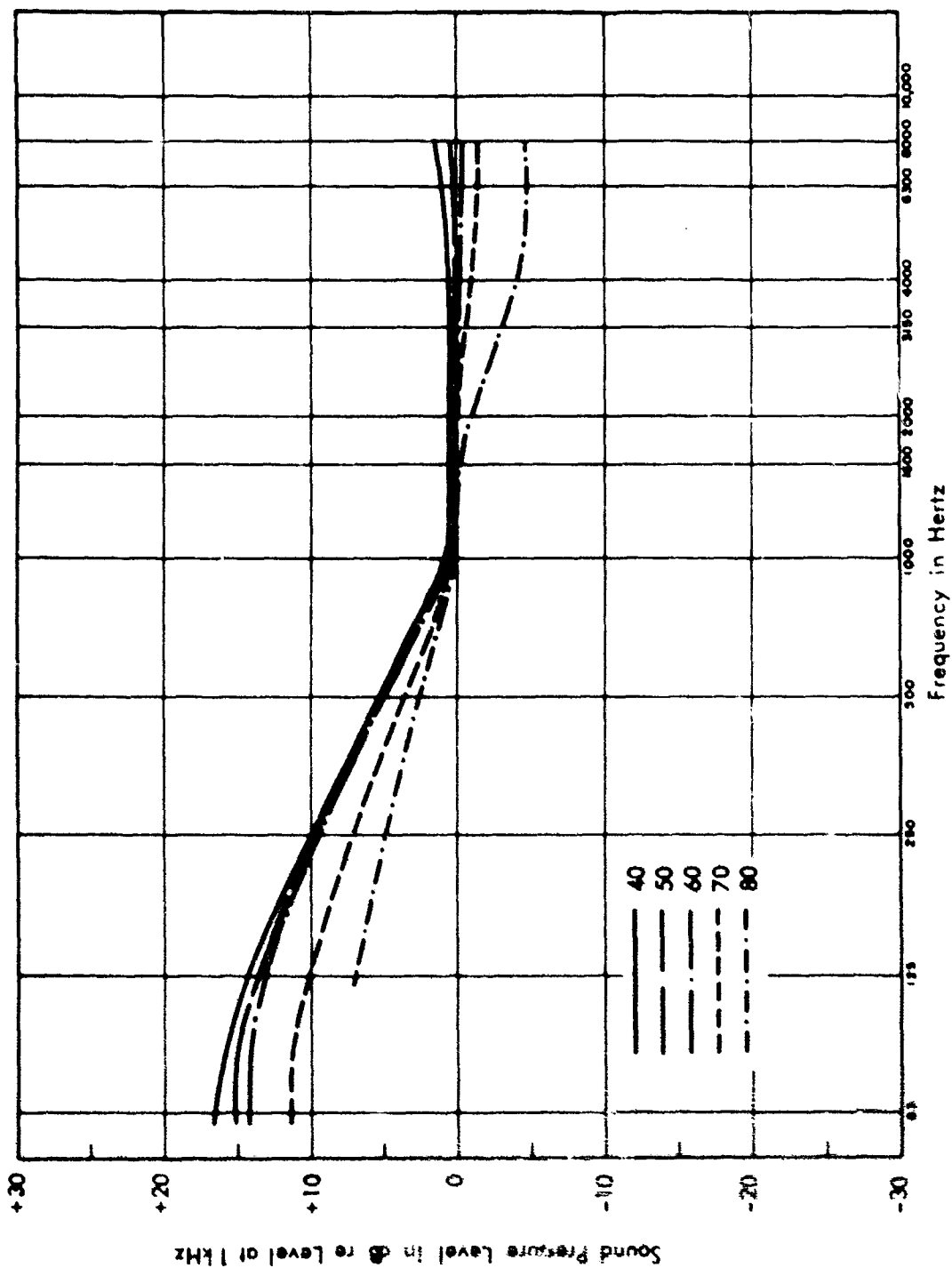
FIGURE 13. COMPARISON OF EQUAL NOISINESS CONTOURS OBTAINED FOR PURE TONE STIMULI AT 10 dB INTERVALS FROM 40 dB TO 80 dB SOUND PRESSURE LEVEL UNDER FREE FIELD (ANECHOIC CHAMBER) CONDITIONS.

Numbers Represent Sound Pressure Levels at 1kHz for a Particular Contour

-24-
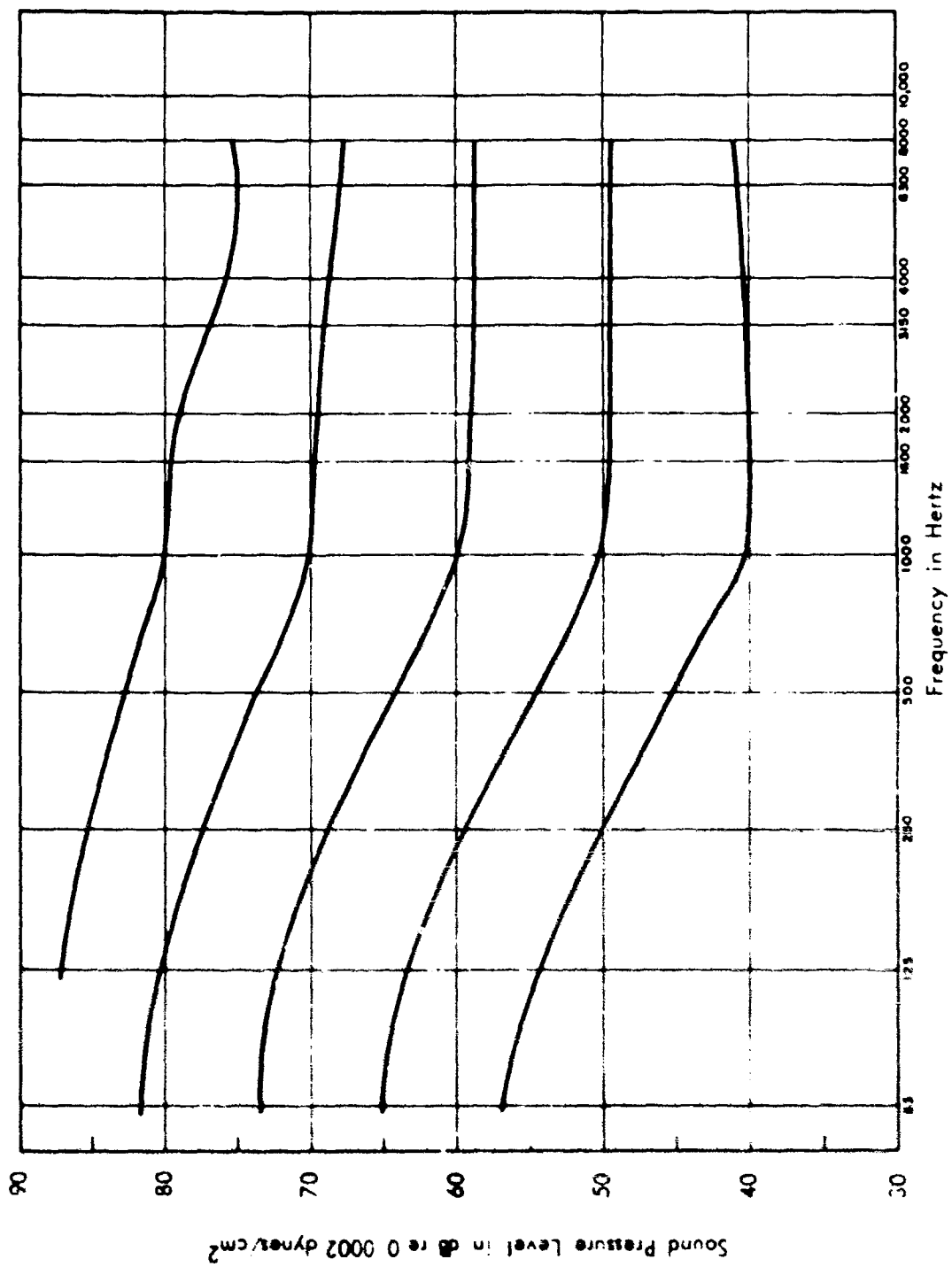
FIGURE 14. SMOOTHED EQUAL NOISINESS CONTOURS FOR PURE TONE STIMULI UNDER FREE FIELD CONDITIONS

The initial test condition in this section utilized one-second samples of the noise stimuli with judgments made in the free-field environment. Under these conditions, the test results in the form of the equal noisiness contours could be compared with the pure tone contours to gain some information on the effects of bandwidth. Also, testing these noise stimuli in the anechoic chamber represents a first approximation of the form of the equal noisiness contours for an idealized outdoor listening situation.

The data obtained from this first series of tests are shown in Figs. 15 and 16. The median values and standard deviations are shown in the same way as the pure tone data. The previous curve smoothing procedure was used and is illustrated in Figs. 17 through 20. The final contours shown in Fig. 20 are the shapes obtained for the specified test stimuli in a free-field environment.

When compared with the pure tone contours in Fig. 14, the contour shapes for the one-third octave bandwidth noise stimuli show more low frequency compression over the range of sound pressure levels and also contain a dip in the region of 3000 Hz. This dip in the equal noisiness contour is similar to the contour shapes from previous investigations (Kryter 1959, Kryter and Pearsons 1963). This similarity is particularly evident at the higher sound pressure levels.

3) Equal Noisiness Contours - One-Third Octave Bandwidth
     Noise with Four-Second Stimulus Duration

The next test condition in this series extended the duration of the test stimuli to four seconds. This test was the first of several undertaken to provide comparisons with existing data on perceived noisiness. The test was conducted in the anechoic chamber using a one-third octave bandwidth pink noise as a test stimulus. The only parameter that was changed was the duration of the test signals, from one second to four seconds. The four-second stimulus duration has been used previously in the investigation of noisiness (Kryter and Pearsons 1963) and was included in the current tests for comparison with existing data.

A total of nine test subjects were chosen randomly from the group of twenty who participated in the previous tests. Three contours were defined in this test at levels of 40, 60 and 80 dB SPL for the 1 kHz noise band used as the standard. The test instructions described previously and shown in Appendix IIC were used for this test.
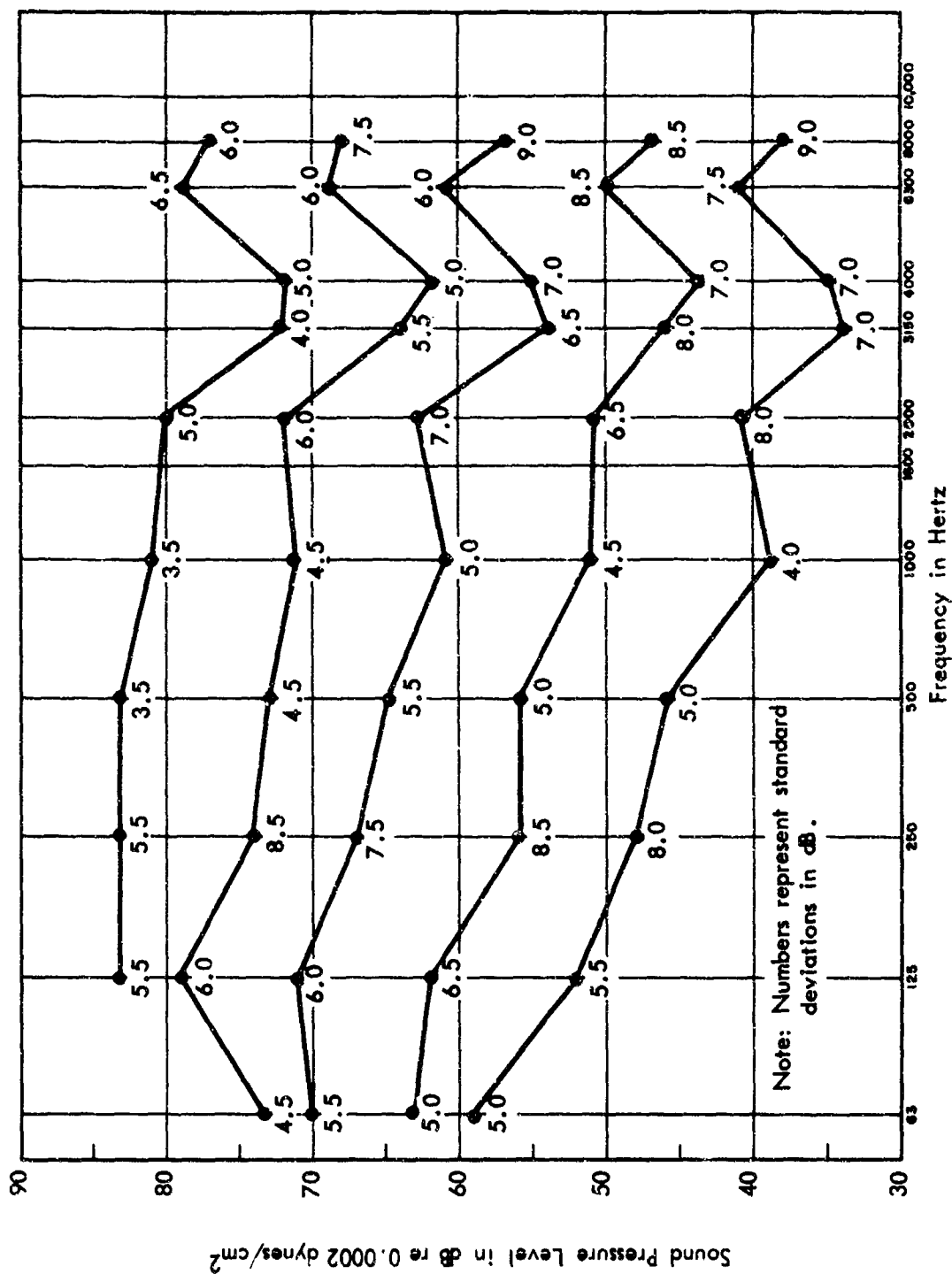
FIGURE 15. EQUAL NOISINESS CONTOURS FOR 1 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE ANECHOIC CHAMBER. BBN NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 18 SUBJECTS. SUBJECT GROUP 1
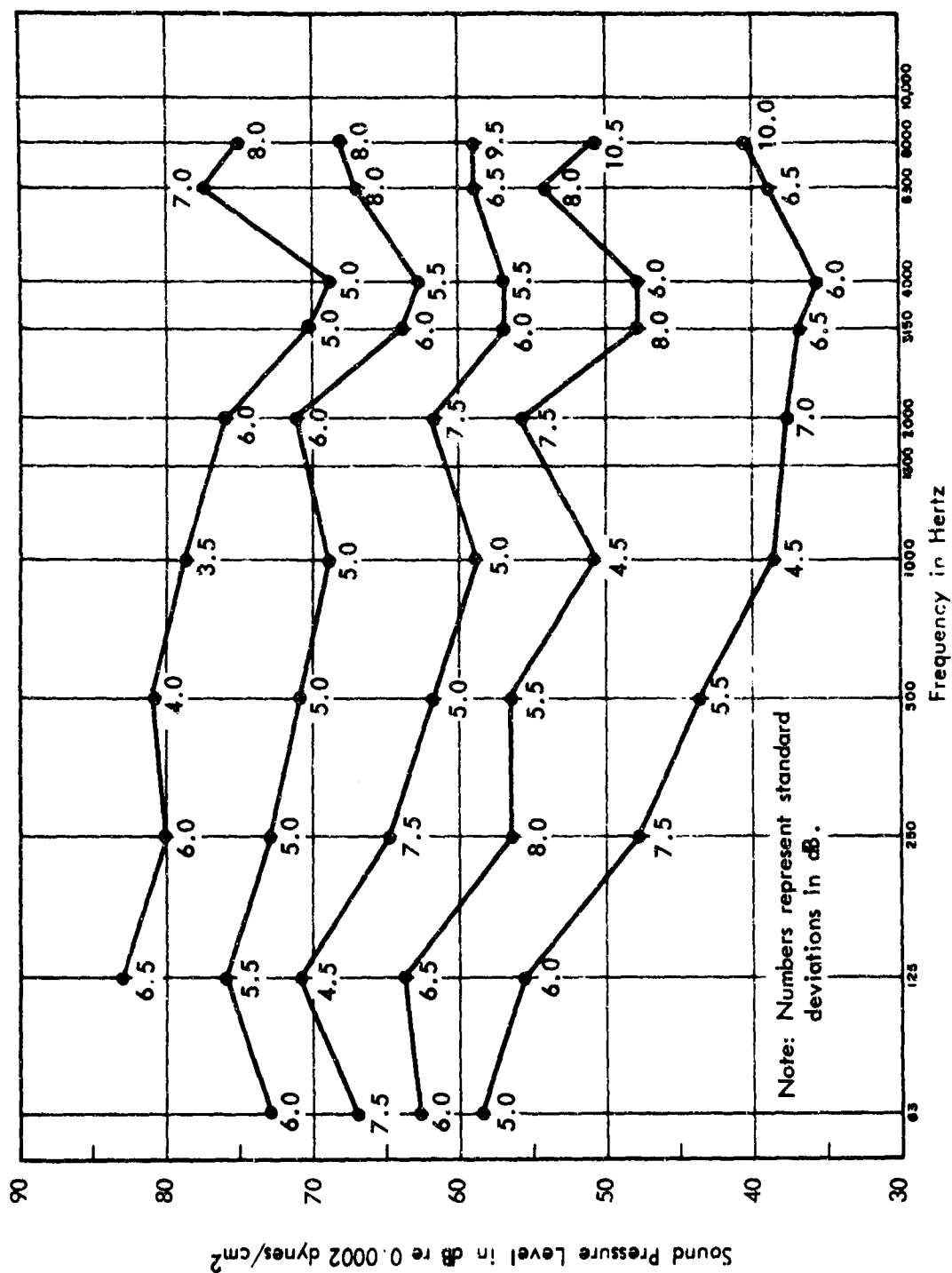
FIGURE 16. EQUAL NOISINESS CONTOURS FOR 1 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE ANECHOIC CHAMBER. BBN NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 17 SUBJECTS. SUBJECT GROUP 1
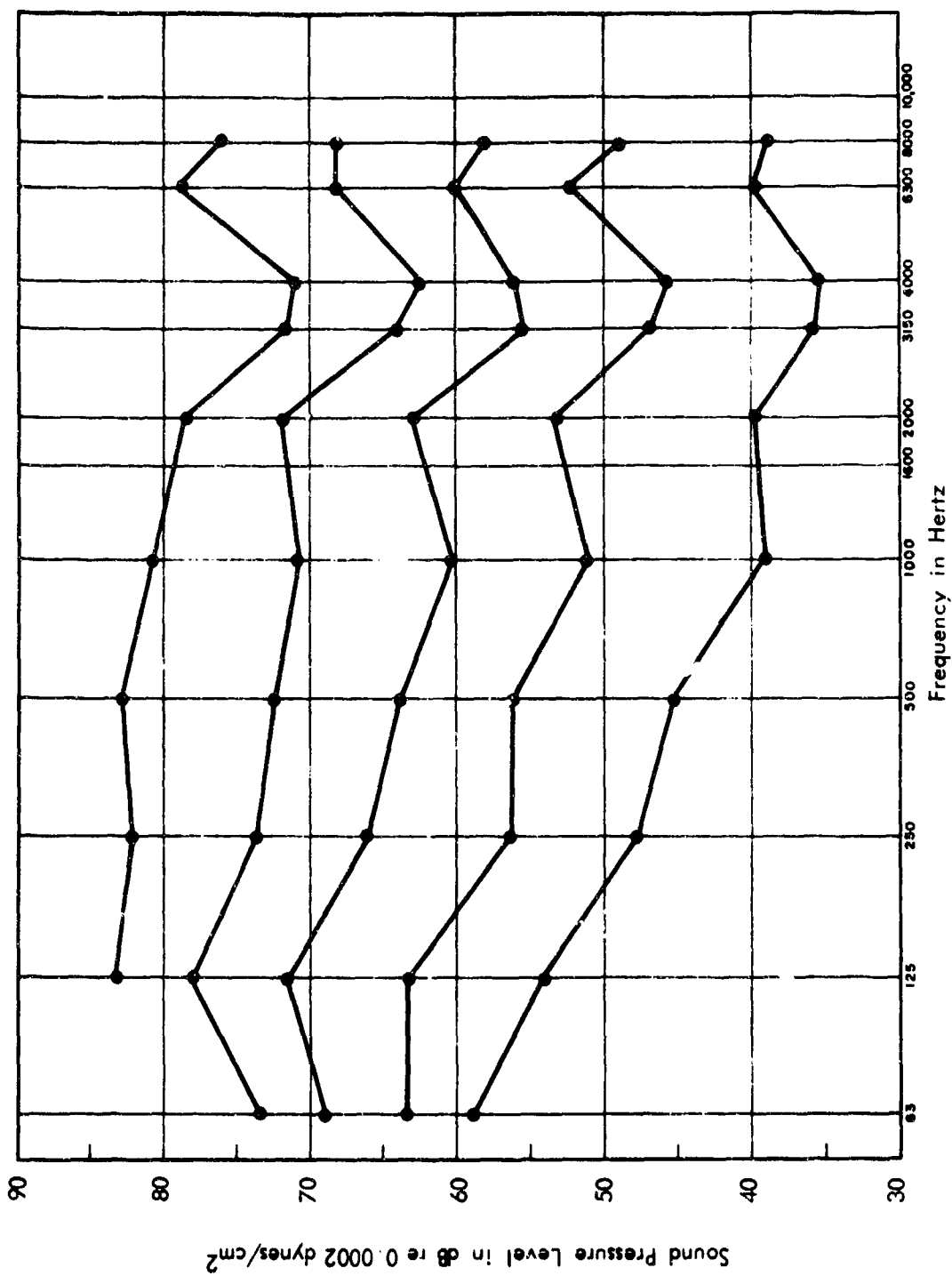
FIGURE 17. SUMMARY OF EQUAL NOISINESS DATA OBTAINED IN THE ANECHOIC CHAMBER FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI. POINTS REPRESENT AND AVERAGE OF DATA FROM FIGURES 15 AND 16.
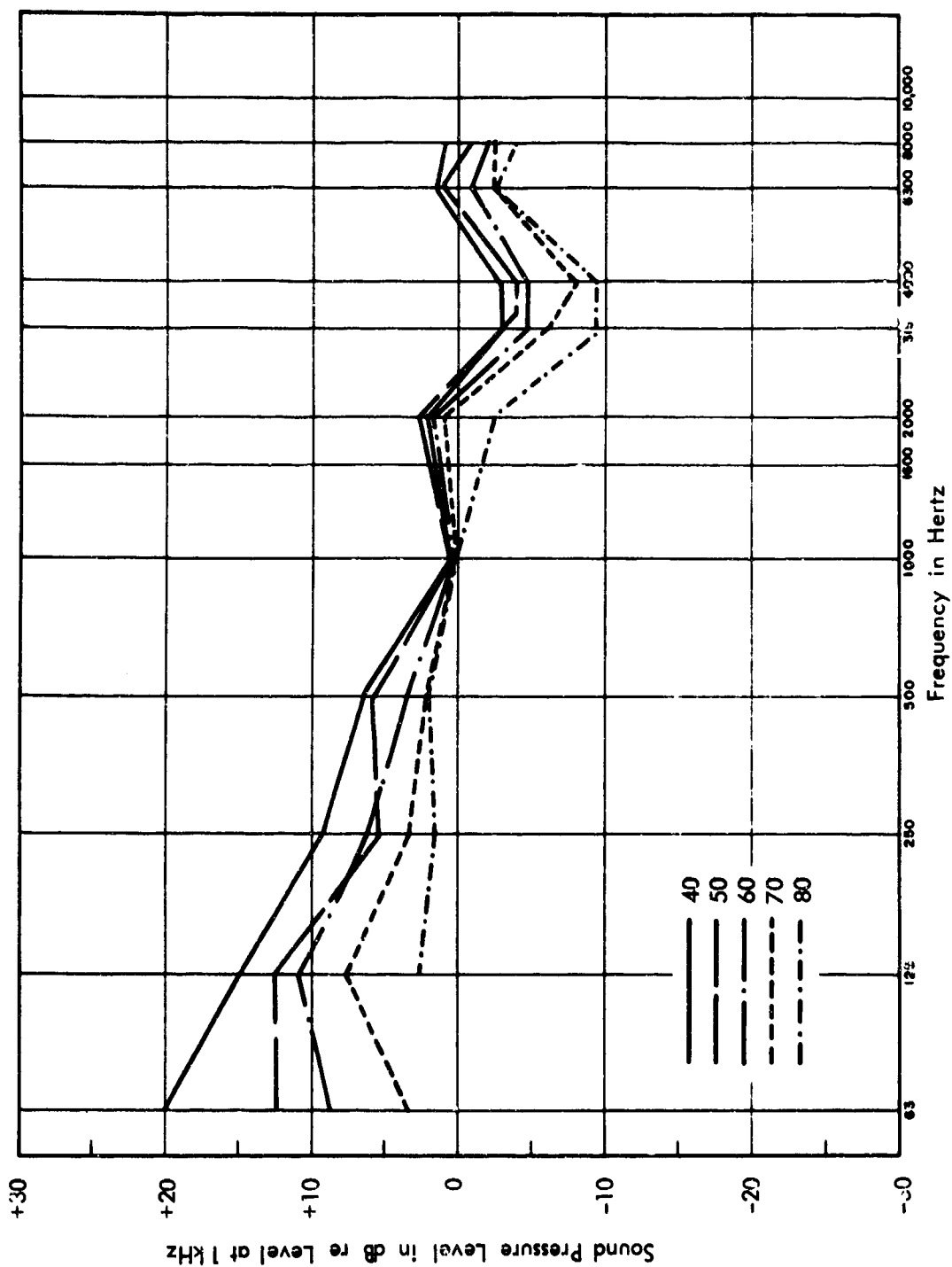
FIGURE 18. COMPARISON OF EQUAL NOISINESS CONTOURS OBTAINED FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI AT 10 dB INTERVALS FROM 40 dB TO 80 dB SOUND PRESSURE LEVEL UNDER FREE FIELD (ANECHOIC CHAMBER) CONDITIONS. CURVES SHOWN ABOVE CONNECT ACTUAL DATA POINTS PRIOR TO SMOOTHING OF THE CONTOURS.
Numbers Represent Sound Pressure Levels at 1kHz for a Particular Contour

-30-
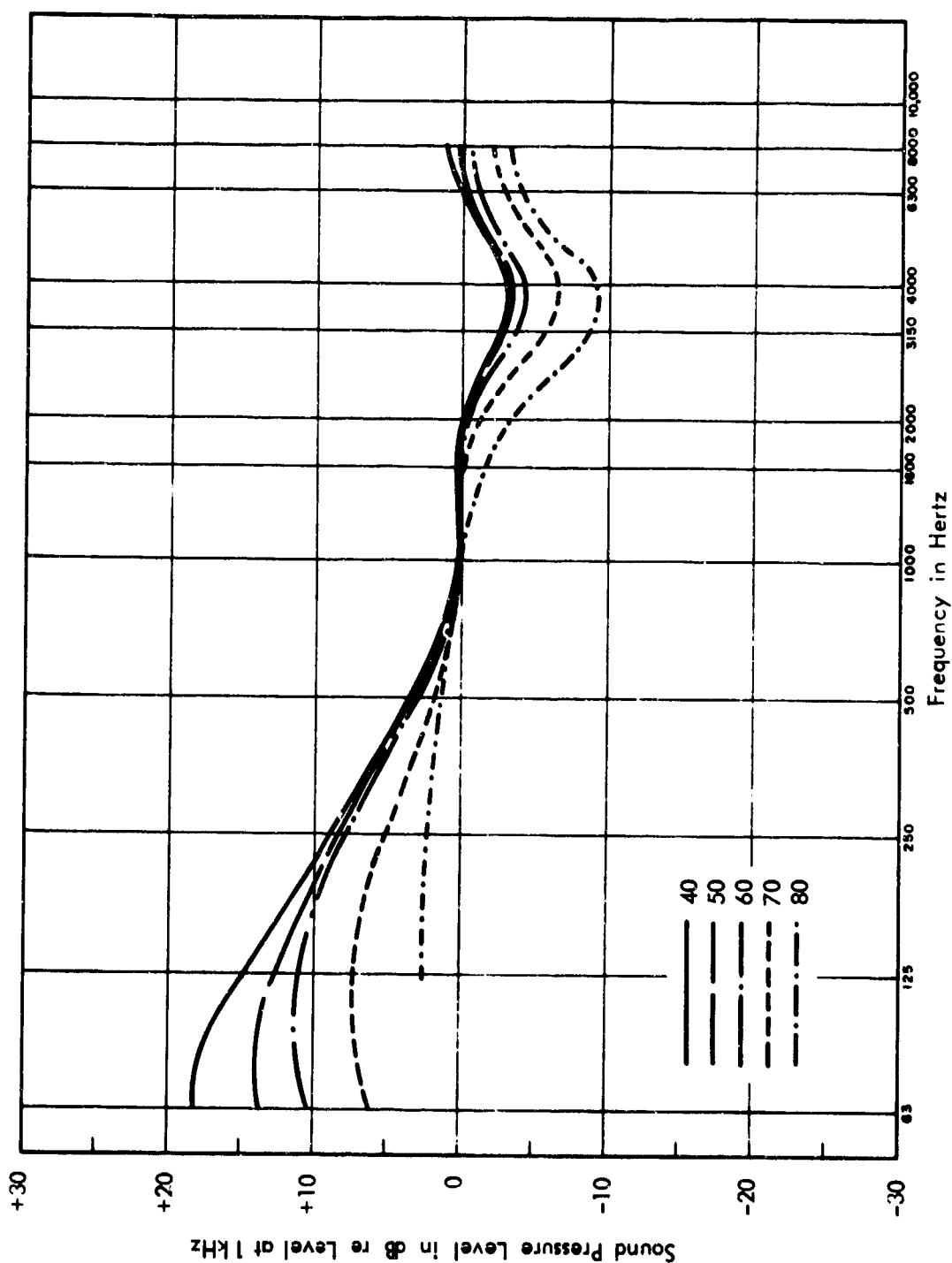
FIGURE 19. COMPARISON OF EQUAL NOISINESS CONTOURS OBTAINED FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI AT 10 dB INTERVALS FROM 40 dB TO 80 dB SOUND PRESSURE LEVEL UNDER FREE FIELD (ANECHOIC CHAMBER) CONDITIONS. Numbers Represent Sound Pressure Levels at 1kHz for a Particular Contour
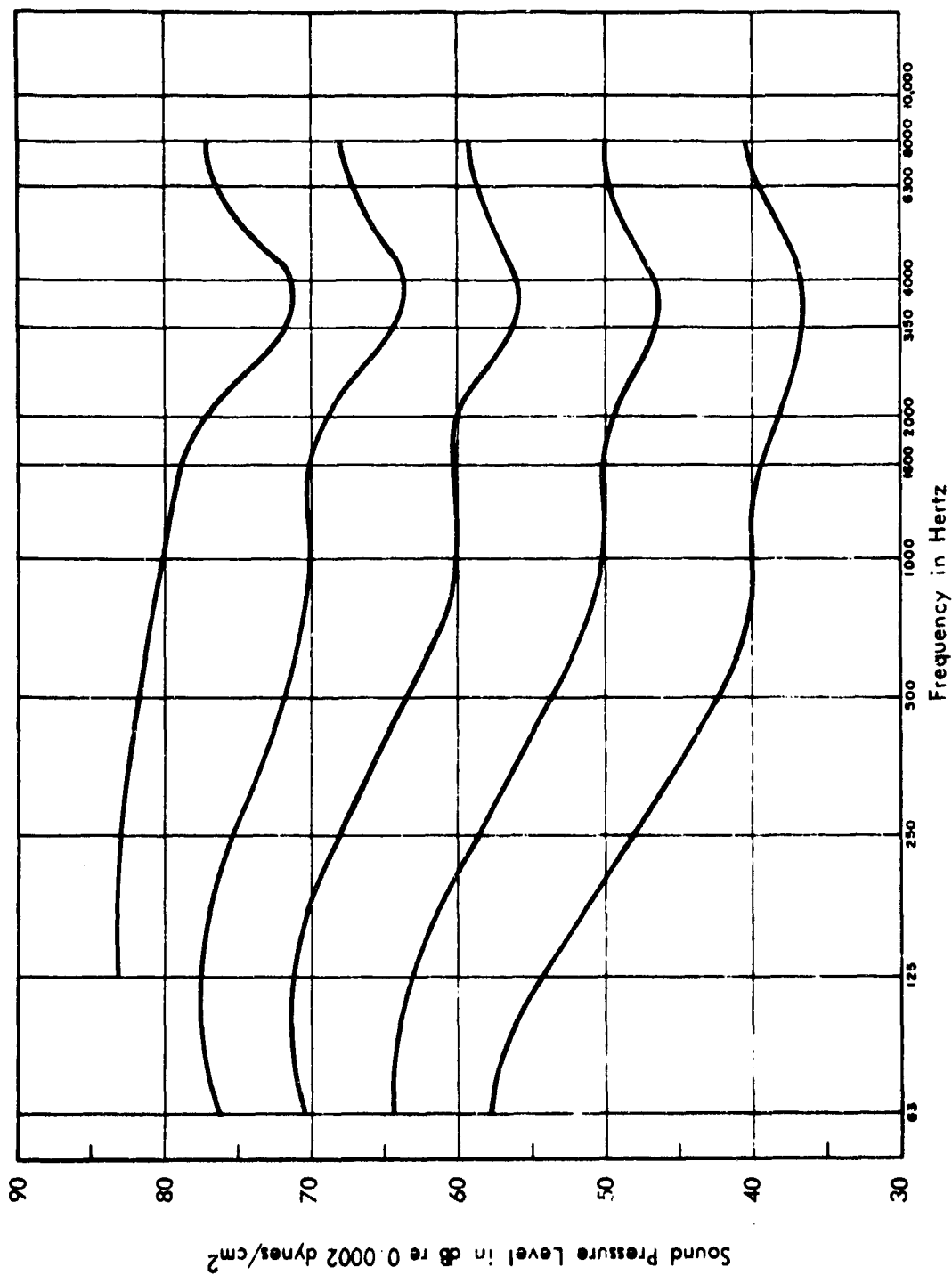
FIGURE 20. SMOOTHED EQUAL NOISINESS CONTOURS FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI UNDER FREE FIELD CONDITIONS

The equal noisiness contours, again plotted as median values for the nine subjects with numerical notation for the standard deviations, are shown in Fig. 21. A statistical comparison of the equal noisiness data for the one-second and four-second stimulus durations was made using a t-test. This involved a frequency-by-frequency comparison at each of the contour levels. No significant differences were found for these two stimulus durations.* It should be noted that this result is only for a condition where the standard and comparison stimuli are the same duration. Previous investigations into the effects of duration (Kryter and Pearsons, 1963; Pearsons 1966) on perceived noisiness have changed the comparison duration while holding the standard constant. Thus, the current findings apply to the absolute rather than relative duration of the standard-comparison stimuli.

4) Equal Noisiness Contours - Two Different Forms of Noisiness Instructions

The conditions for the final set of comparisons made in the free-field environment were identical to the preceding tests with the exception of the test instructions. A new group of ten subjects, described as Group II in Table III,** were given test instructions (Appendix II-E) taken from Kryter and Pearsons (1963) for the determination of the existing equal noisiness contour. The results of these judgments are presented in Fig. 22. Five contours were determined at levels of 40, 50, 60, 70 and 80 dB SPL for the 1 kHz noise band standard. (As in the previous test, these results were not included in determining the smoothed-free-field noise band contours of Fig. 20.)

A comparison was made of the contours obtained for four-second duration noise stimuli tested in the anechoic chamber (Figs. 21 and 22) using the two different forms of the noisiness instructions shown in Appendix II. Again, the t-test was applied at each frequency for each of the contours with no significant differences found at any of the points. This finding would appear to indicate that the precise wording of the instructions for perceived noisiness do not affect the shape of the equal noisiness contours.

---

*   The statistical measure of significance is taken as the 95% confidence level.

** Table III (Pg. 35) describes each of the test groups referenced in the text.

FIGURE 21. EQUAL NOISINESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND
NOISE STIMULI TESTED IN THE ANECHOIC CHAMBER. BBN NOISINESS INSTRUCTIONS
USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 7 SUBJECTS CHOSEN
AT RANDOM FROM GROUP 1.

TABLE III
SUBJECT GROUP TYPES

Group I	- Subjects had been used previously in some psycho-acoustic testing. Average age 20.1 years. Group population comprised of 10 male, 10 female subjects, ranging in age from 17 to 27 years
Group II	- Subjects had been used previously in some psycho-acoustic testing. Average age 19.3 years. Group population comprised of 3 male, 7 female subjects ranging in age from 18 to 22 years.
Group IV	- Subjects never before used in psychoacoustic tests. Average age 20.7 years. Group population comprised of 7 male, 3 female subjects, ranging in age from 19 to 23 years.
Group V	- Subjects had been used previously in psycho-acoustic tests; however, different personnel than in Groups I through IV. Average age 20.8 years. Group population comprised of 4 male, 6 female subjects, ranging in age from 17 to 24 years.

NOTE: Group III subjects were employed in the tests described in FAA Report DS-67-22.

FIGURE 22. EQUAL NOISINESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE ANECHOIC CHAMBER. KRYTER-PEARSONS NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 10 SUBJECTS. SUBJECT GROUP II.

5) Equal Noisiness Contours - One-Third Octave Bandwidth
   Noise in a Diffuse Field Environment

The remainder of the equal noisiness tests were conducted
in a semi-reverberant room used to approximate a diffuse
field listening environment. The test conditions were
designed to establish a basic set of equal noisiness contours
for a one-third octave band noise stimulus judged in a
diffuse field. In addition, the effects of instructional
set were evaluated. This included a test of the differences
between loudness and noisiness for these test conditions.

The test results for a one-second duration, one-third
octave band noise stimulus in a diffuse sound field are
shown in Fig. 23. The noisiness instructions in Appendix II-C
were used in this test. The group of nine subjects for this
test were randomly selected from Group I of Table III. Since
it was possible to achieve somewhat higher sound pressure
levels in the semi-reverberant room, the equal noisiness
contours were defined at levels of 60, 70, 80, 90 and 100 dB
SPL for the 1 kHz noise band standard.

6) Equal Noisiness Contours - Loudness vs Noisiness
   Instructions

The next set of four tests utilized a stimulus duration
of four seconds. The test instructions in these four
judgment tests were taken from Kryter and Pearsons (1963).
Test conditions were set to determine the effect of basing
the comparisons on the subjective attribute of loudness rather
than noisiness. Test Groups IV and V, described in Table III,
were given instructions for judging either loudness or noisiness.
The noisiness instructions were those given in Appendix II-E.
These were also used as loudness instructions (Appendix II-D)
by substituting this latter attribute for noisiness throughout
the instructions.

The equal noisiness and equal loudness contours obtained
for the specified test conditions are presented in Figs. 24
through 28. These data for loudness and noisiness were com-
pared using the t-test at each frequency and for each contour.
The results showed no significant difference in the results
for the two different instructions under these conditions.

The data for all tests conducted in the semi-reverberant
room were averaged to produce the smooth contours which are
developed in Figs. 29 through 32. For the test conditions
described in this section, the family of curves shown in
Fig. 32 represent the shape of the contours for a diffuse
field environment, characteristic of an indoor listening
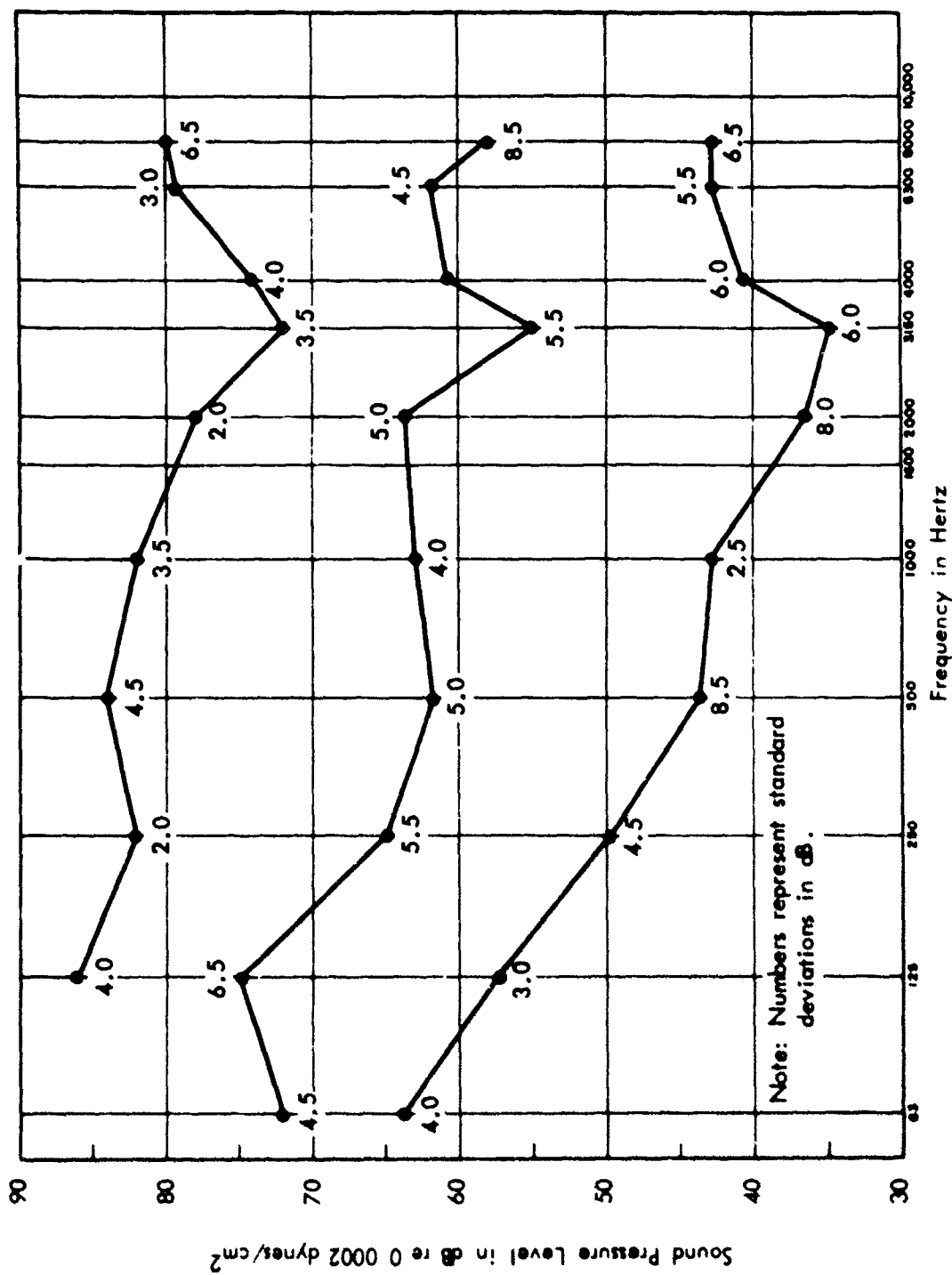situation.

-37-
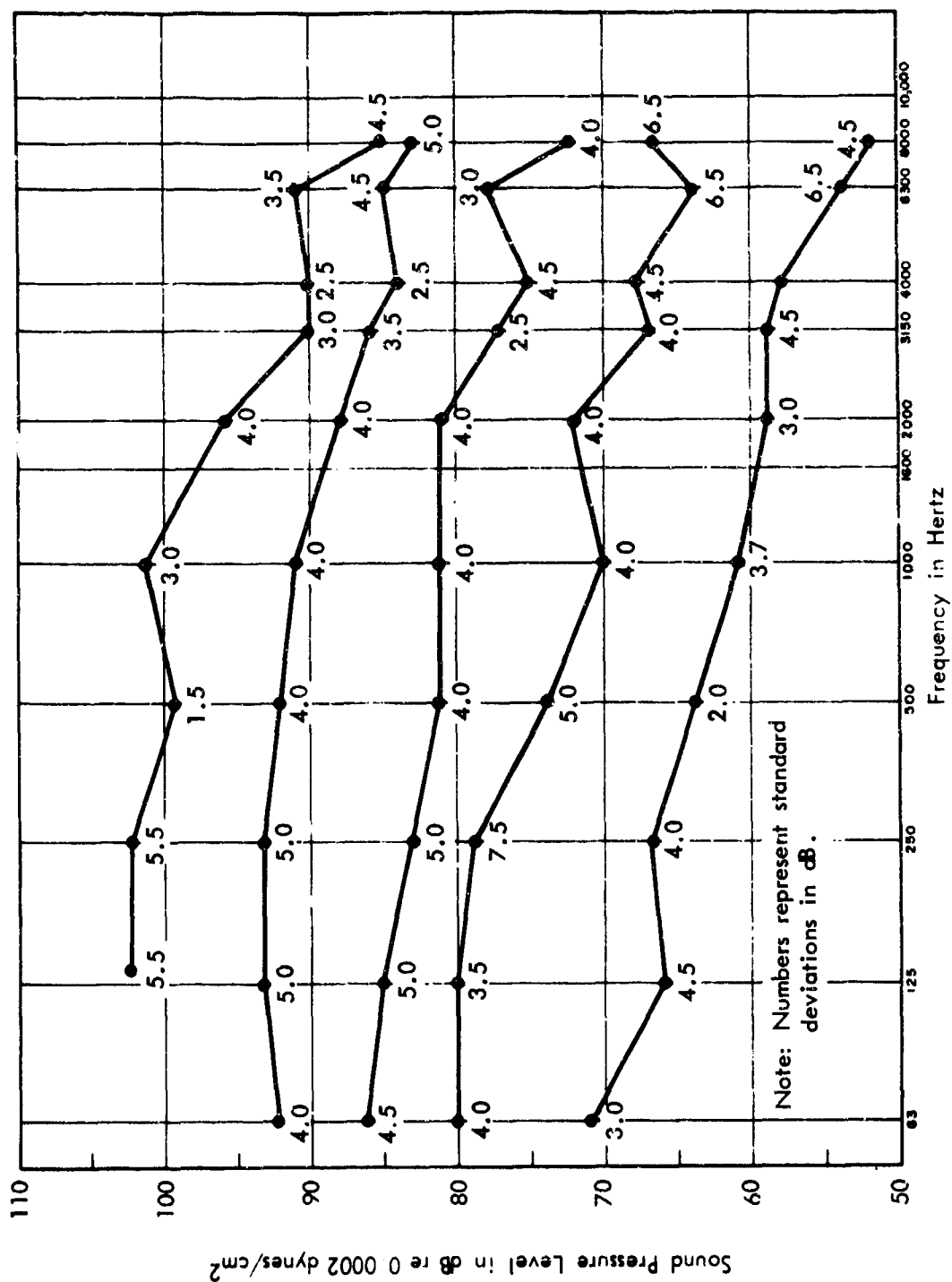
FIGURE 23. EQUAL NOISINESS CONTOURS FOR 1 SECOND, ONE THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE SEMI-REVERBERANT ROOM. BBN NOISINESS INSTRUC-TIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 9 SUBJECTS CHOSEN AT RANDOM FROM GROUP I.
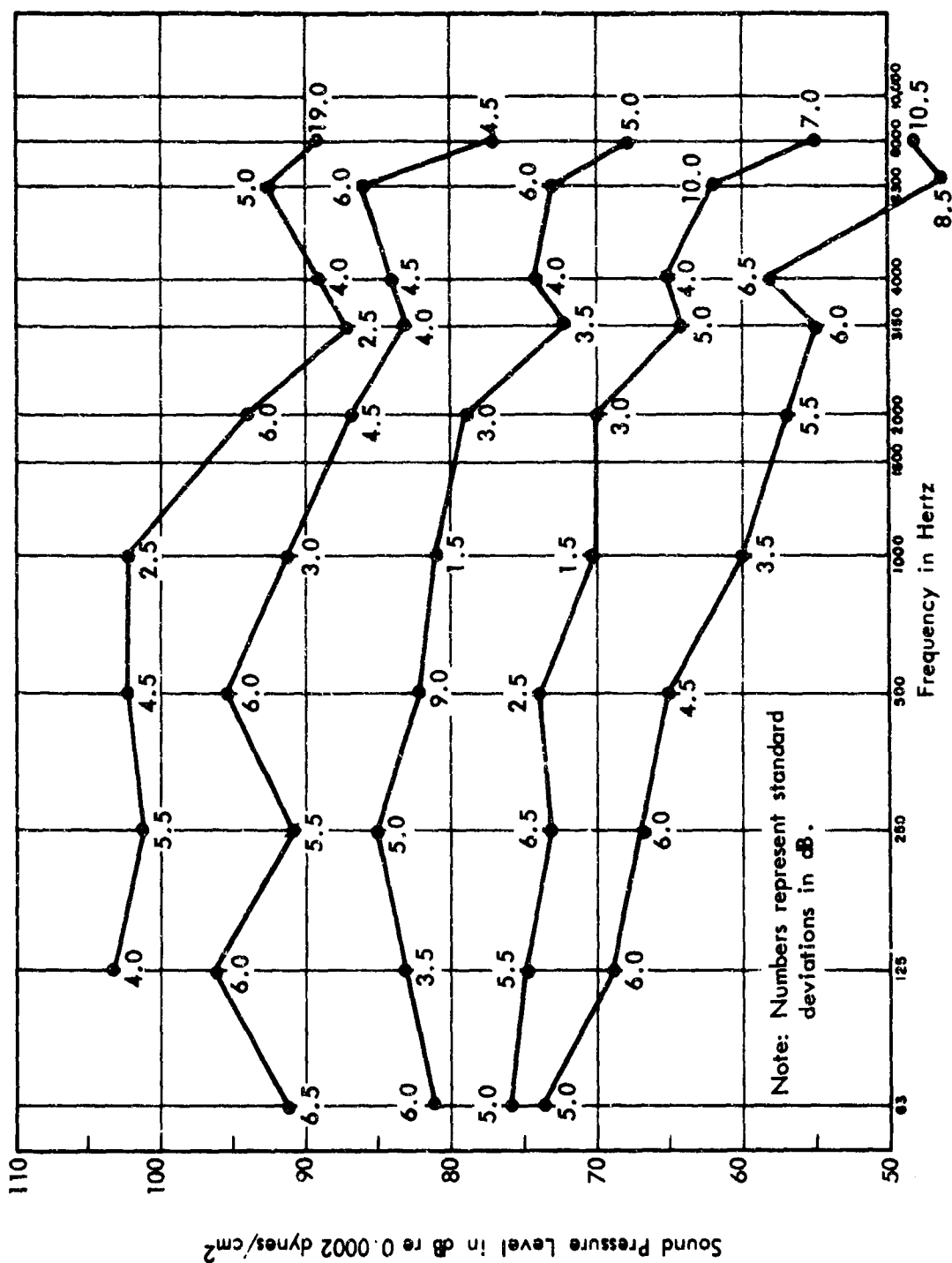
FIGURE 24. EQUAL NOISINESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE SEMI-REVERBERANT ROOM. KRYTER-PEARSONS NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 10 SUBJECTS. SUBJECT GROUP II.
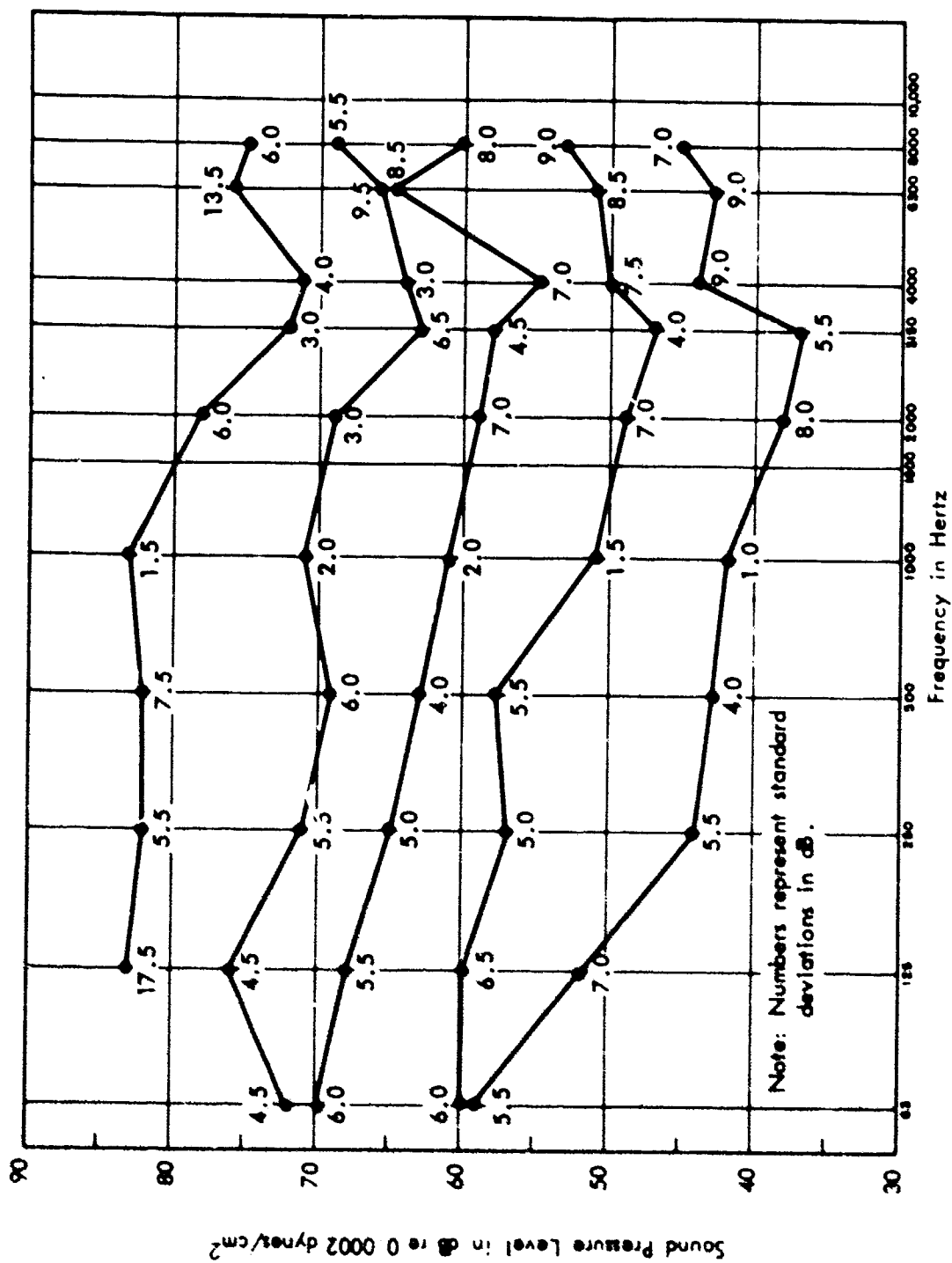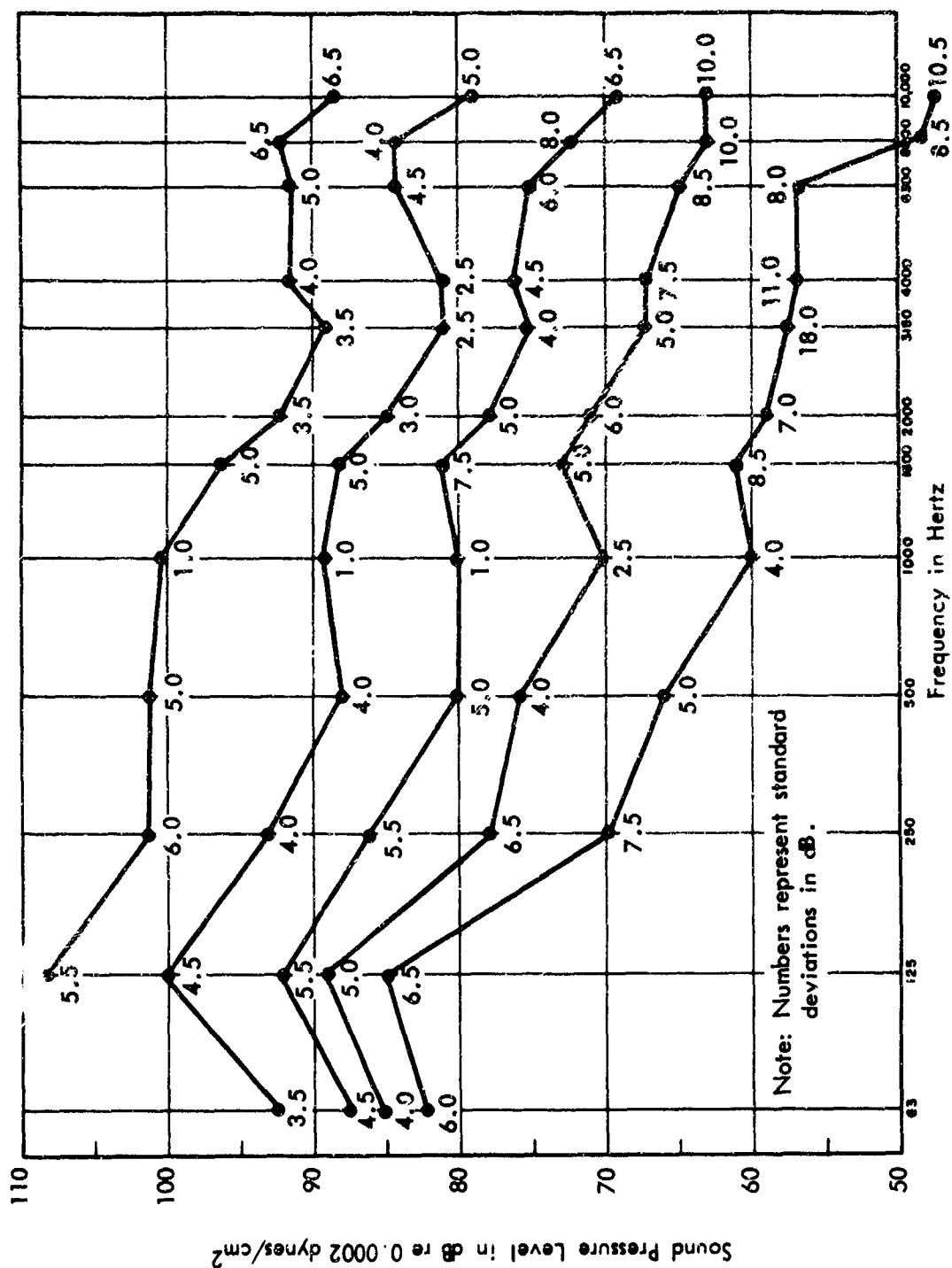
FIGURE 25. EQUAL NOISINESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE SEMI-REVERBERANT ROOM. KRYTER-PEARSONS NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 10 SUBJECTS. SUBJECT GROUP IV.

-40-
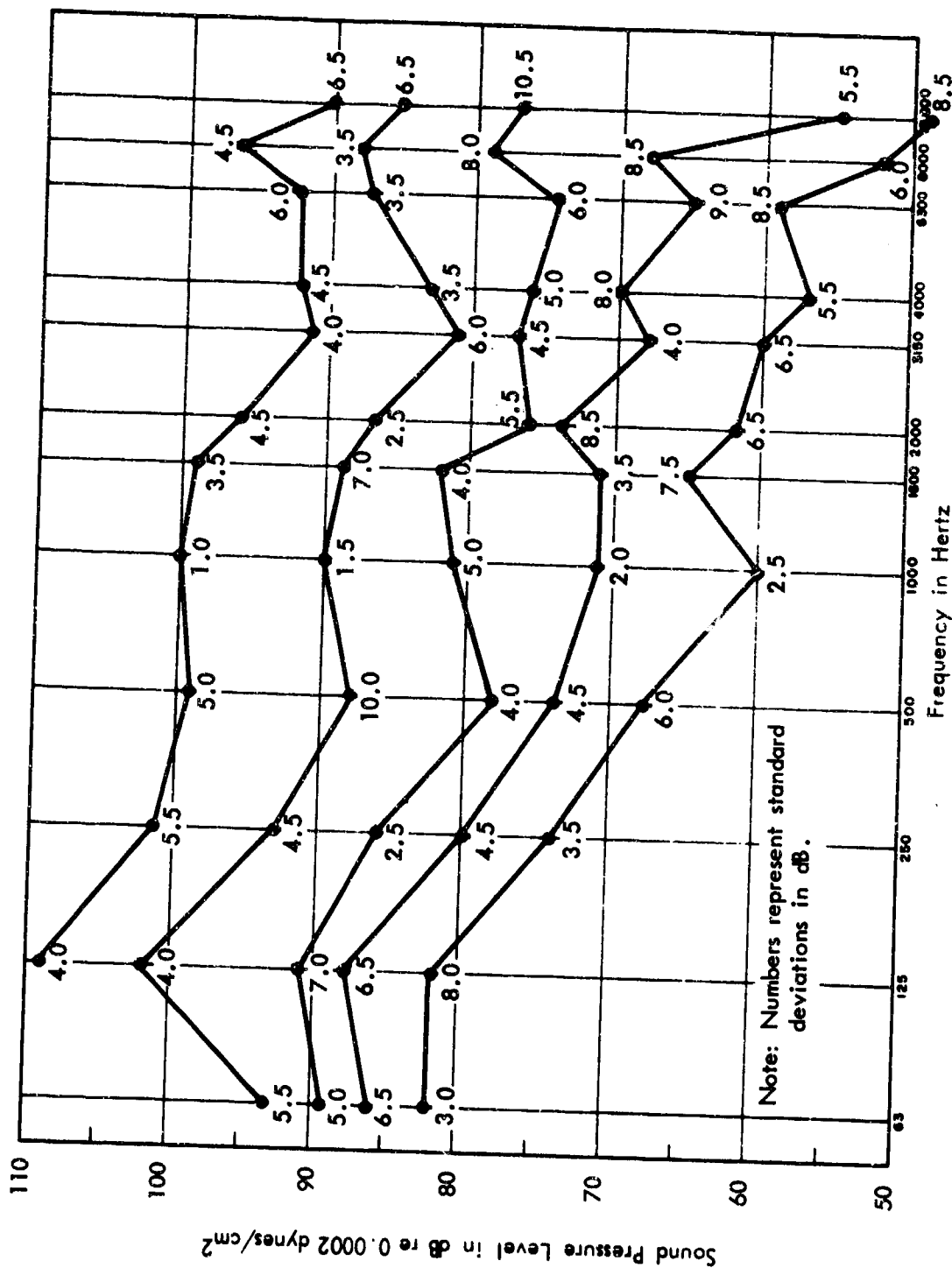
FIGURE 26. EQUAL LOUDNESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE SEMI-REVERBERANT ROOM. KRYTER-PEARSONS LOUDNESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 10 SUBJECTS. SUBJECT GROUP IV.
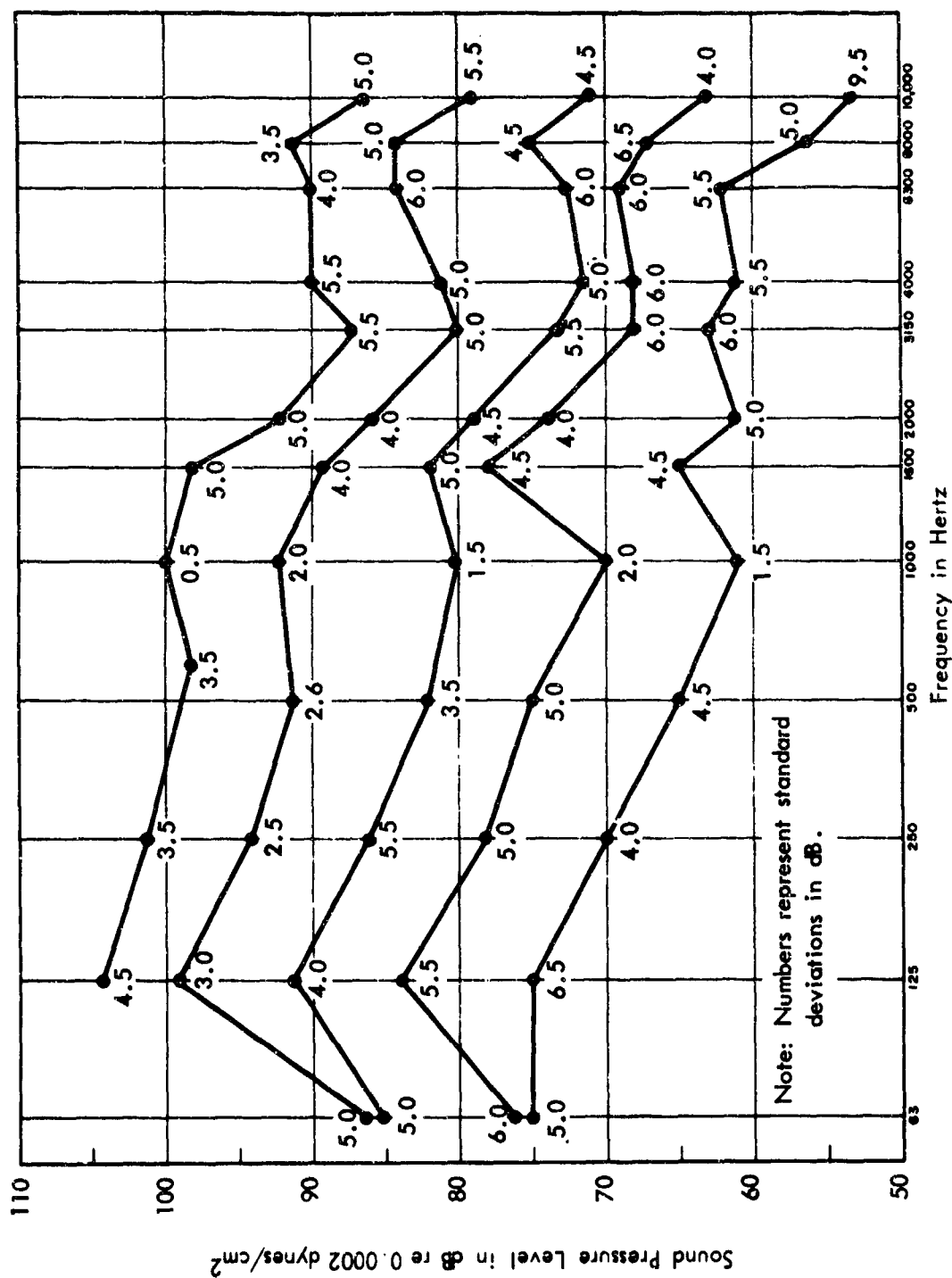
FIGURE 27. EQUAL LOUDNESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE SEMI-REVERBERANT ROOM. KRYTER-PEARSONS LOUDNESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 10 SUBJECTS. SUBJECT GROUP V.

Note: Numbers represent standard deviations in dB.
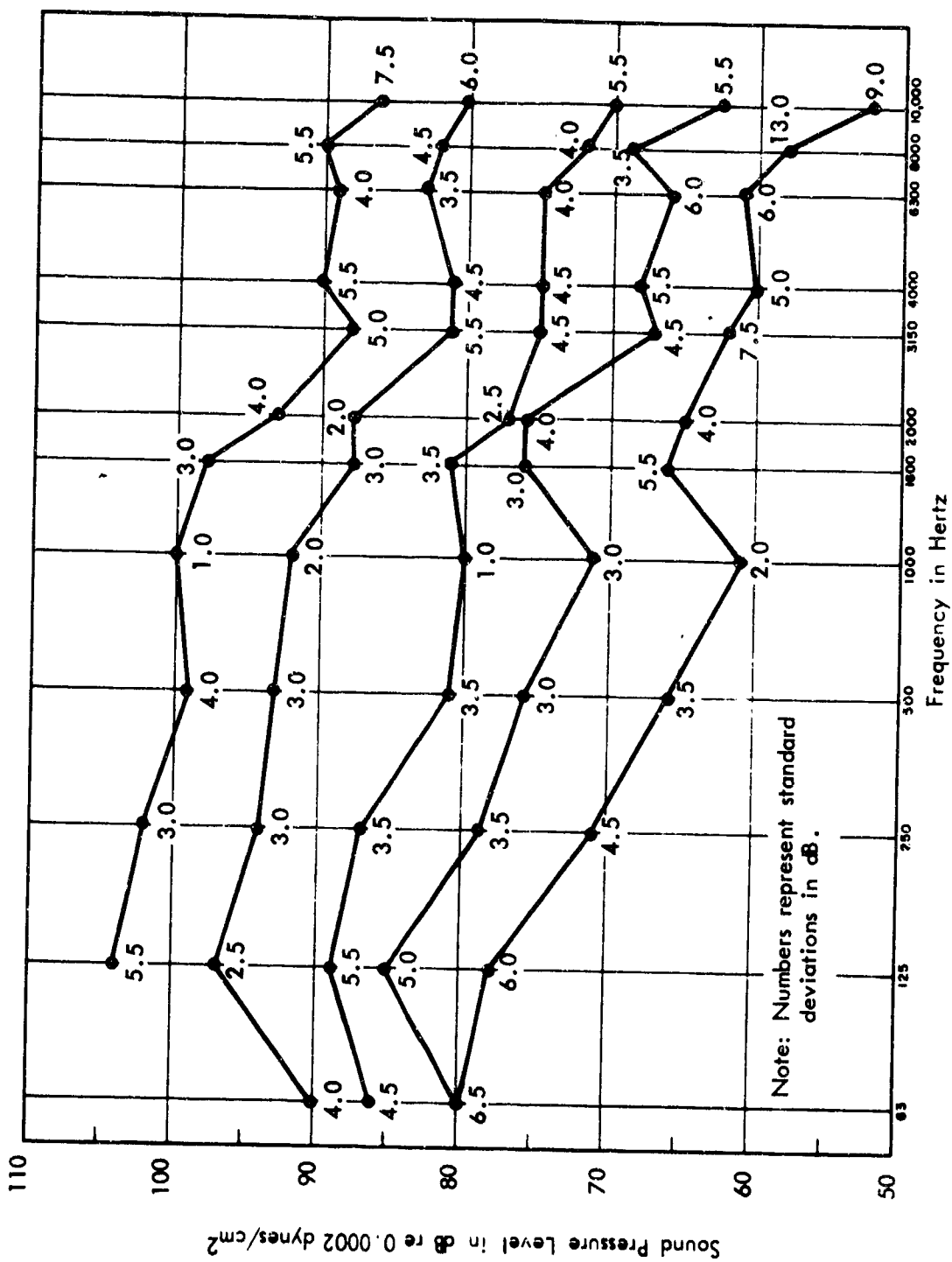
FIGURE 28. EQUAL NOISINESS CONTOURS FOR 4 SECOND, ONE-THIRD OCTAVE BAND NOISE STIMULI TESTED IN THE SEMI-REVERBERANT ROOM. KRYTER-PEARSONS NOISINESS INSTRUCTIONS USED. DATA POINTS REPRESENT THE MEDIAN JUDGMENTS OF 10 SUBJECTS. SUBJECT GROUP V.
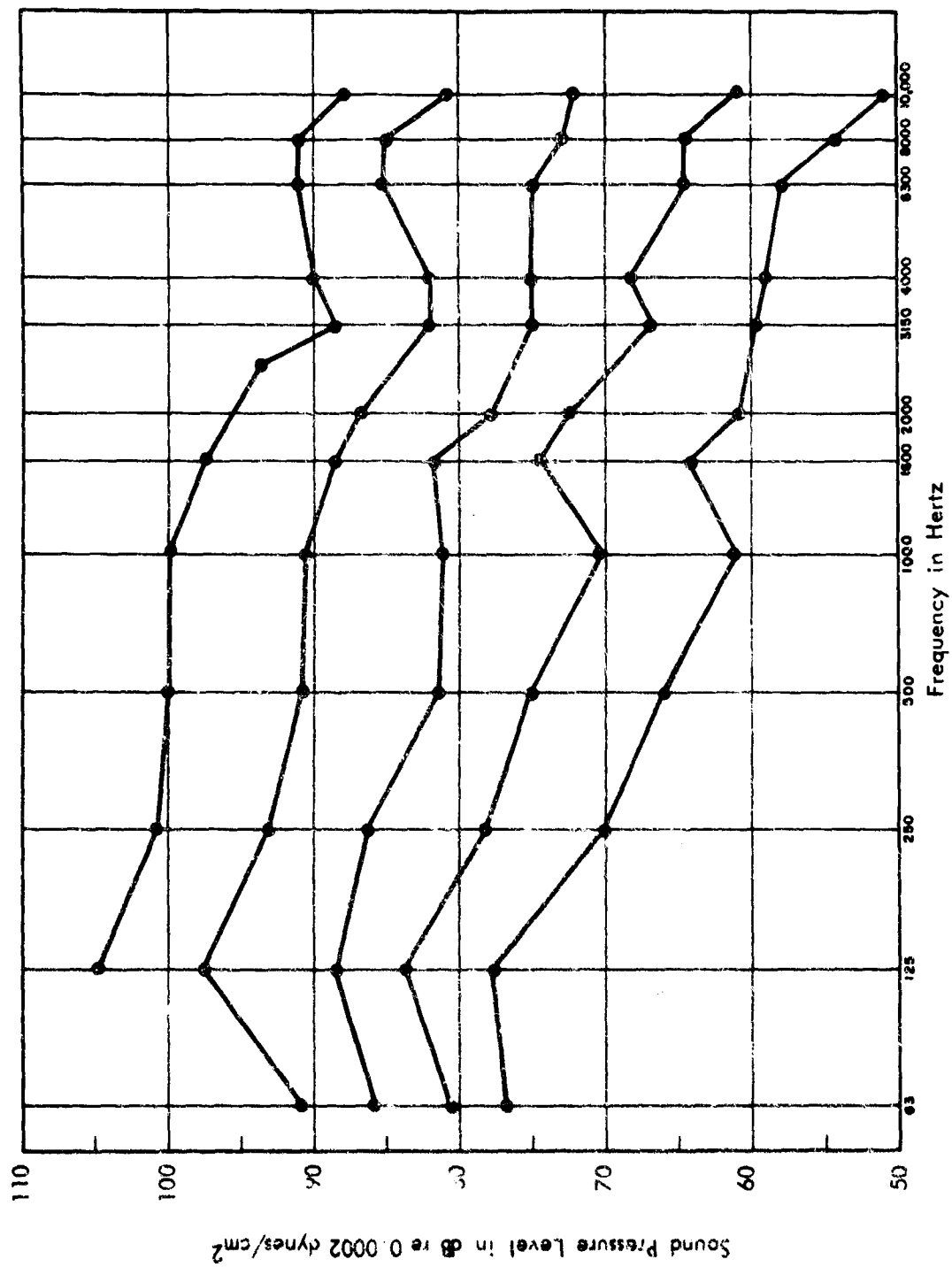
FIGURE 29. SUMMARY OF AVERAGED EQUAL LOUDNESS AND NOISINESS DATA OBTAINED IN A SEMI-REVERBERANT ROOM FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI. POINTS REPRESENT AN AVERAGE OF DATA FROM FIGURES 23, 24, 25, 26, 27, AND 28.

-44-
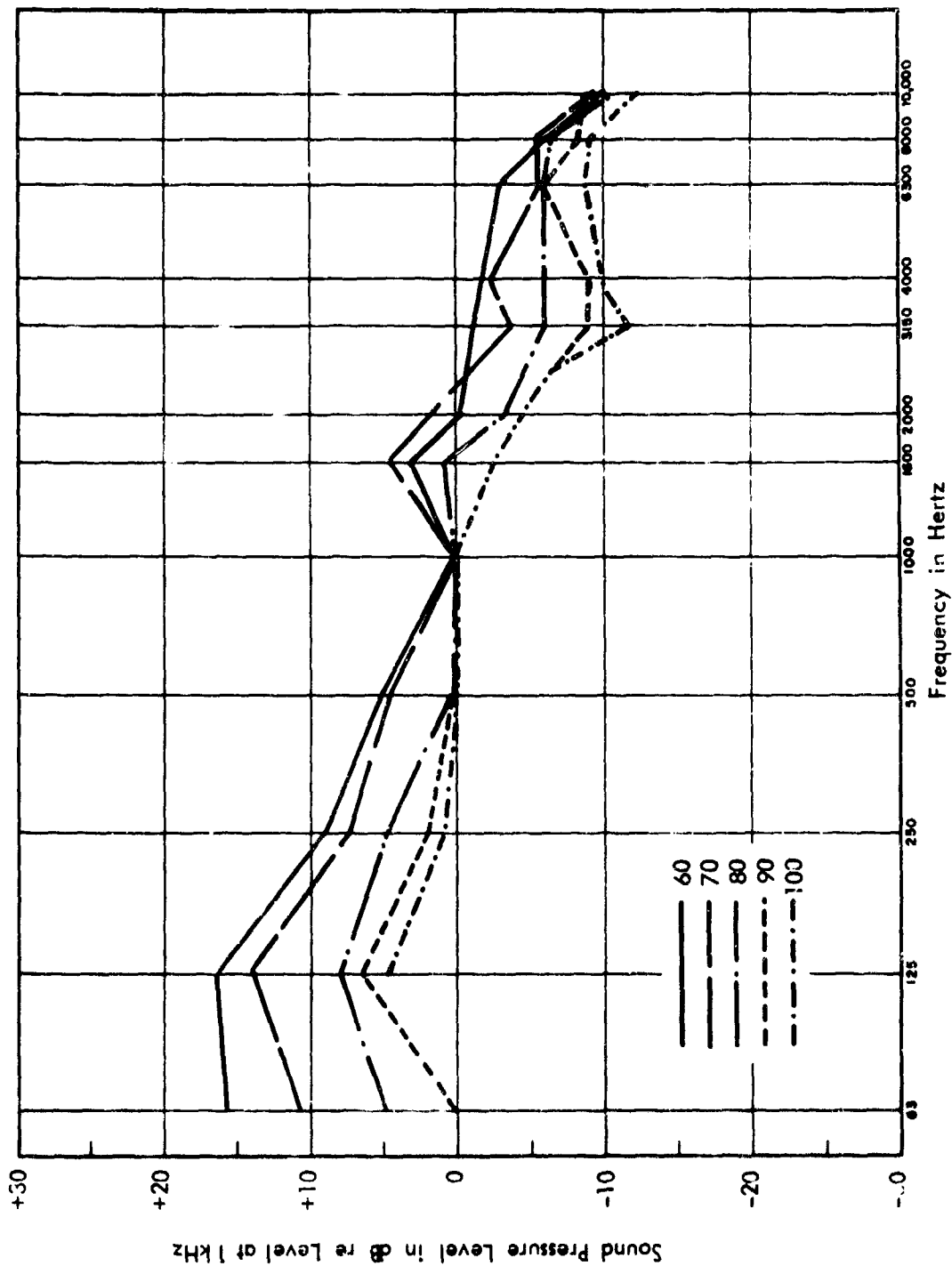
FIGURE 30. COMPARISON OF EQUAL NOISINESS CONTOURS OBTAINED FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI AT 10 dB INTERVALS FROM 60 dB TO 100 dB SOUND PRESSURE LEVEL UNDER DIFFUSE FIELD (SEMI-REVERBERANT ROOM) CONDITIONS. CURVES SHOWN ABOVE CONNECT ACTUAL DATA POINTS PRIOR TO SMOOTHING OF THE CONTOURS. Numbers Represent Sound Pressure Levels at 1kHz for a Particular Contour.
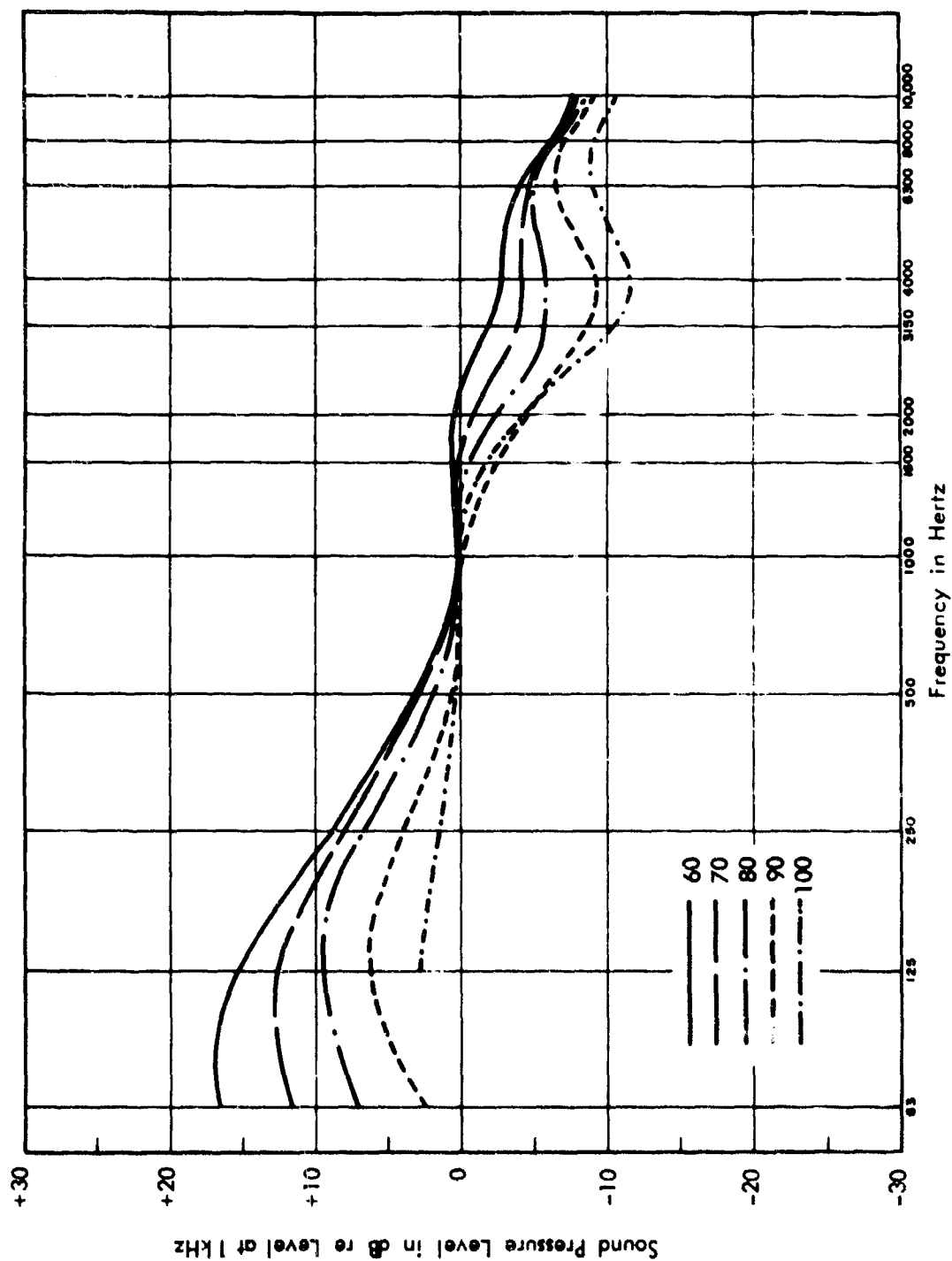
FIGURE 31. COMPARISON OF EQUAL NOISINESS CONTOURS OBTAINED FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI AT 10 dB INTERVALS FROM 60 dB TO 100 dB SOUND PRESSURE LEVEL UNDER DIFFUSE FIELD (SEMI-REVERBERANT ROOM) CONDITIONS. Numbers Represent Sound Pressure Levels at 1kHz for a Particular Contour
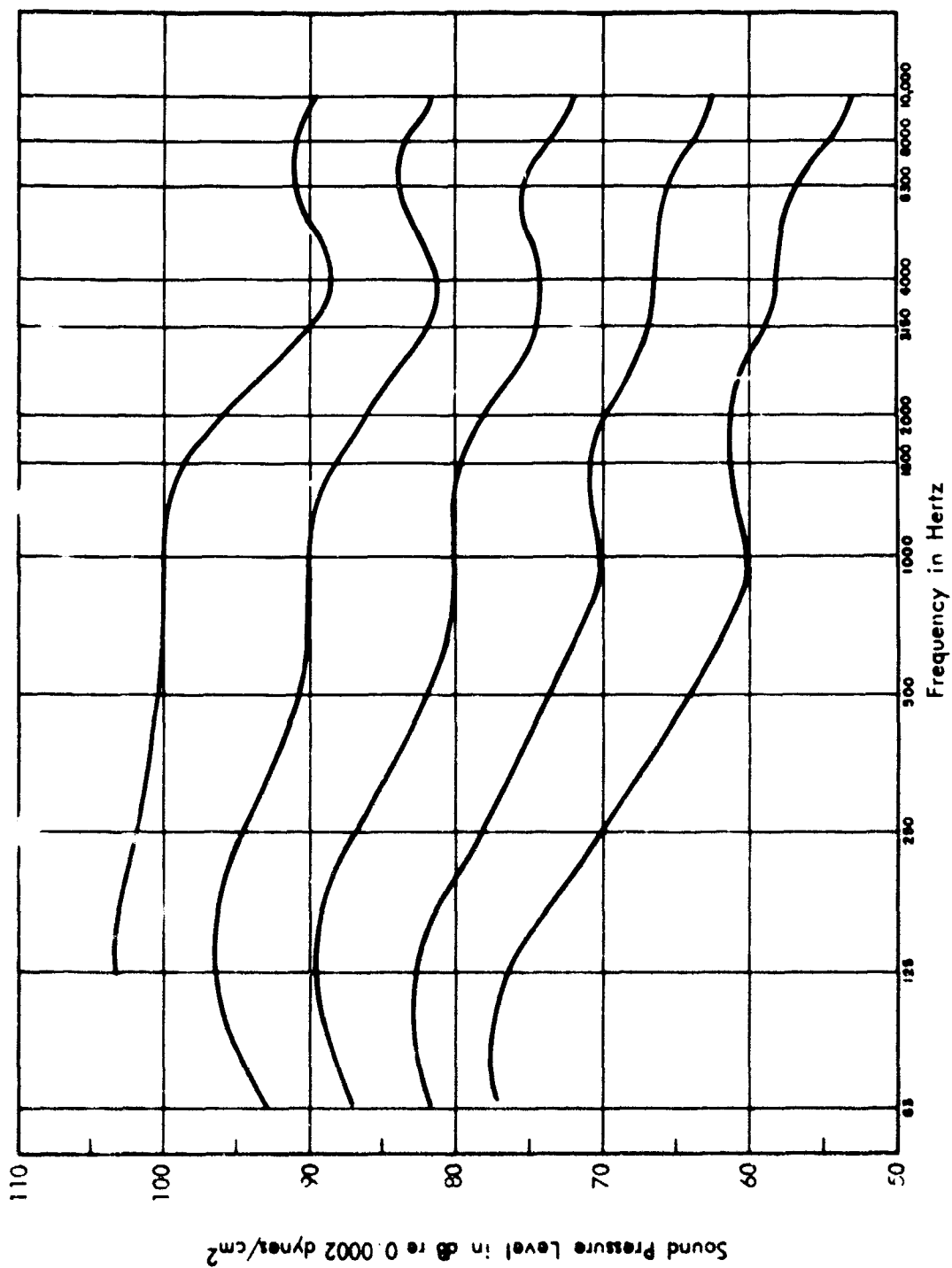
FIGURE 32. SMOOTHED EQUAL NOISINESS CONTOURS FOR 1/3 OCTAVE BANDWIDTH NOISE STIMULI UNDER DIFFUSE FIELD CONDITIONS

-47-

The diffuse field equal noisiness contours are similar in shape to those obtained under free-field conditions. The difference in the contours occurs in the region of 8000 Hz where the diffuse field contours turn downward unlike the free-field contours which are rising through this part of the frequency spectrum.

D. Discussion

As noted earlier (and further discussed in Appendix III) it would not appear that data related to the growth of noisiness, i.e., the increase in judged noisiness as a function of sound intensity, are particularly critical to the PNL calculation procedure. If this assumption is correct, the important information for the calculation procedures is then related to equal noisiness contour shape, bandwidth effects and the influence of the upward spread of masking in a complex noise spectrum.

The experimentation described in this section has been directed toward a definition of the equal noisiness contours for a variety of test conditions. Since the shape of the equal noisiness contours are incorporated in the noisiness and loudness calculation procedures it is of interest to compare the contours developed in the current tests with those used in some of the calculation procedures. The most widely used current method for calculating the relative acceptability of complex noise spectra is the scheme implemented by Kryter (1959, 1963), termed Perceived Noise Level (PNL).

The experimentally determined basis of the PNL scheme is the equal noisiness contour determined at a sound pressure level of approximately 90 dB (Kryter and Pearsons, 1963). This contour shape was originally extrapolated to higher and lower levels to form the family of curves relating noisiness to sound intensity. These curves are compared with the experimentally determined contours from this investigation in Fig. 33. The curve at the 90 dB SPL obtained from the 1963 judgment tests is nearly identical to the contour at 90 dB SPL (1 kHz noise band) from the current tests. At lower sound pressure levels (for the 1 kHz standard) the existing contour shapes deviate from those determined in the current tests. Insofar as most PNL calculations for aircraft noise are concerned with the higher sound pressure levels (90-100 dB), these differences in contour shape may not significantly affect the PNdB values.
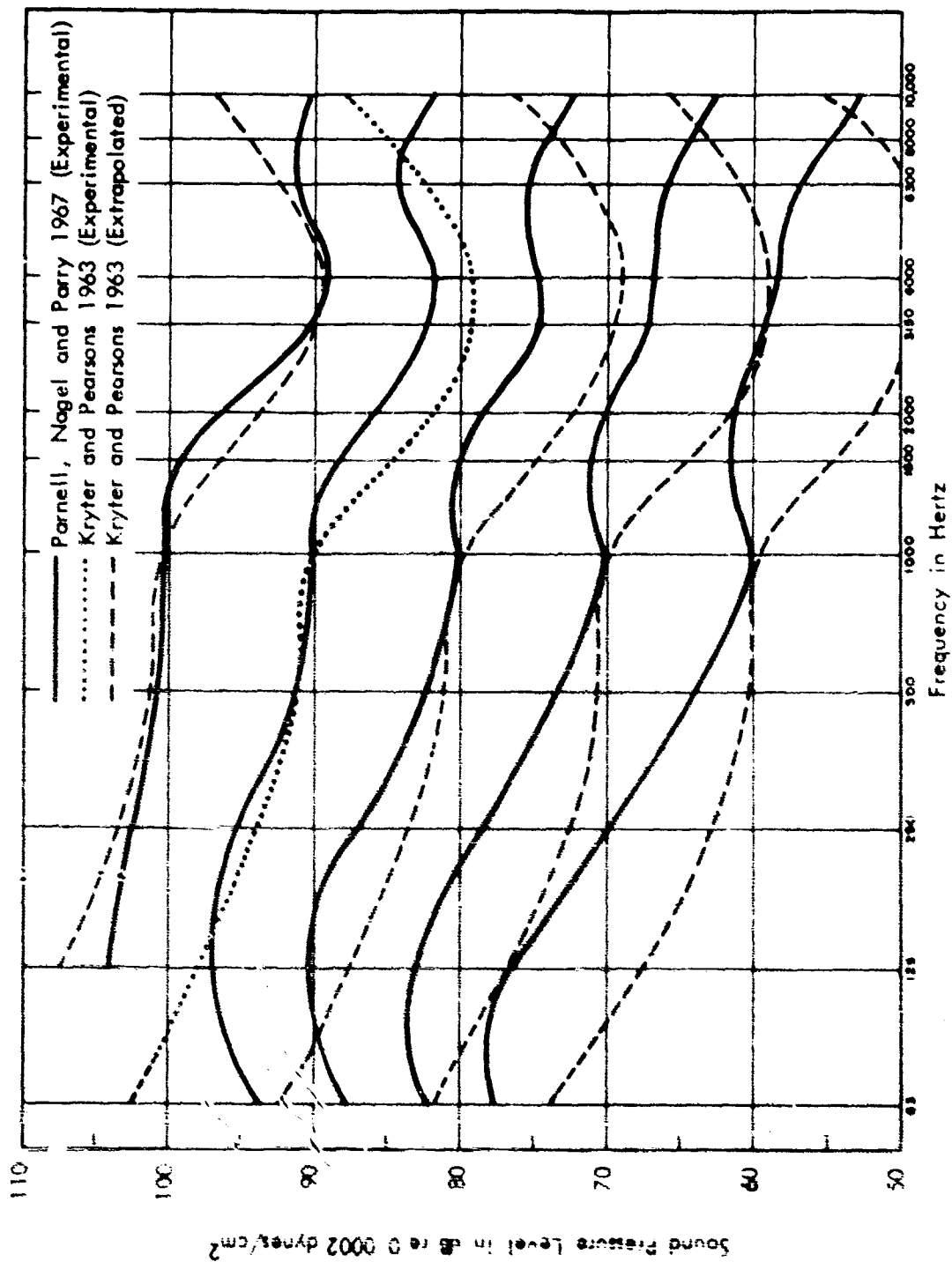
FIGURE 33. COMPARISON OF CURRENT DIFFUSE FIELD EQUAL NOISINESS CONTOURS
WITH THOSE OF KRYTER AND PEARSONS (1963)

-49-

While past investigations have produced reported
subjective differences between the attributes of loudness
and noisiness, it has not been possible to demonstrate
any consistent difference in the present laboratory tests.
As seen in Fig. 34, the equal noisiness curves from this
investigation closely resemble the equal loudness data of
Robinson and Whittle (1964). It is possible that the state-
of-the-art in formulating test instructions for judging
the different attributes of a complex noise are inadequate
for extracting such differences or a consistent and
predictable basis. As a result, test subjects may be
evaluating some generalized attribute such as acceptability
for the noise.

As noted in a previous section of this report, different
equal noisiness contour shapes were obtained for free-field
and diffuse-field listening conditions (Figs. 20 and 32).
A comparison of the differences for these two listening
conditions is shown in Fig. 35. The solid curve represents
differences between the two environments for loudness
judgments and the broken curve shows the same comparison
for the noisiness data from the current investigation.

FIGURE 34. COMPARISON OF SMOOTHED ONE THIRD OCTAVE BAND FREE FIELD
EQUAL NOISINESS CONTOURS AS DETERMINED IN THE PRESENT STUDY WITH
OCTAVE BAND FREE FIELD EQUAL LOUDNESS CONTOURS OBTAINED BY
ROBINSON AND WHITTLE (1964). HEAVY LINE REPRESENTS
RESULTS OF CURRENT TESTS
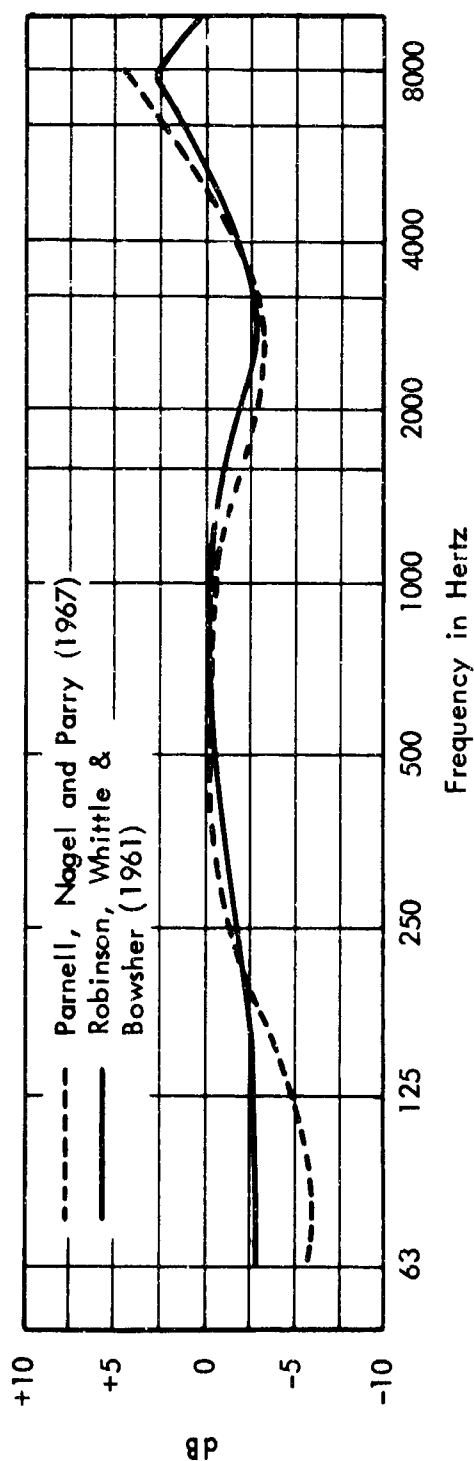
Note: In the above graph, the difference in SPL for equal sensation levels at 1000 Hz is arbitrarily assumed to be 0 dB to facilitate comparison with data of the previous investigation.

FIGURE 35. DIFFERENCE BETWEEN SOUND PRESSURE LEVELS OF FREE FIELD AND DIFFUSE FIELD JUDGMENTS FOR EQUAL SENSATION LEVELS. THE ROBINSON, WHITTLE AND BOWSHER DATA ARE AT EQUAL LOUDNESS AND THE COMPARISON FROM THE CURRENT TESTS ARE AT EQUAL NOISINESS.

IV. SUMMARY AND CONCLUSIONS

The growth of noisiness has been measured for a 1 kHz tone and for octave bands of noise centered at 1 kHz. Test results indicate that this growth function is essentially the same for tones and noise at 1 kHz but is highly dependent on test method. Except for the low reference level (50 dB SPL), the results of the adjustment tests were between 8.5 dB and 14.3 dB (average 11.5 dB) for doubling or halving the perceived noisiness of the test stimuli. At the 50 dB SPL reference level, an average increase of 16.7 dB is required for twice noisiness.

The magnitude estimation tests resulted in consistently larger values than those above for the growth of noisiness. These values ranged from 20-27 dB increase in sound pressure level for twice noisiness at the 70 dB SPL reference and from 14-20 dB at the 90 dB SPL reference. These values varied according to the reference number used by the subject as a basis for the magnitude estimation. Again, no differences in the growth of noisiness for tones and noise were observed.

To determine the growth of noisiness at frequencies other than 1 kHz equal noisiness contours were determined for selected acoustical environments and test stimulus conditions. These contours are shown for:

1) Pure tones in a free-field environment.

2) One-third octave bands of noise in a free-field environment.

3) One-third octave bands of noise in a diffuse field environment.

In addition, the equal noisiness contours were determined for both one-second and four-second stimulus durations and were compared with equal loudness contours obtained in this investigation under identical diffuse field listening conditions. The different stimulus durations were included to allow comparisons with previous tests of both loudness and noisiness.

During the course of this investigation the observation was made that, for purposes of calculating the relative noisiness of different spectra, the actual value used for the growth of noisiness may not significantly affect the resulting comparison. Calculations of the PNL of several typical noise spectra with different spectrum shapes have been made using

growth functions of 3 dB, 5 d3, 10 dB, 20 dB and 30 dB per doubling of noisiness. The results show relative differences between these spectra of 2 PNdB or less using the different growth functions.

The following conclusions have been drawn from the results of the current investigations:

1) Values for the growth of noisiness are strongly dependent on test method, i.e., adjustment vs magnitude estimation. The growth rate at 1 kHz from the adjustment tests averaged 11.5 dB per doubling of perceived noisiness while the magnitude estimation results showed an increase of approximately 20 dB required for twice noisiness.

2) The specific value used for the noisiness growth function does not appear to significantly affect the calculation of the relative acceptability of different noise spectra.

3) At the higher reference levels (90-100 dB SPL) the equal noisiness contours from this investigation are similar to the curves used in current calculation procedures.

4) No significant differences were found in the equal noisiness contours between the two different stimulus durations, one-second and four-seconds, or between the loudness and noisiness instructions under current test conditions.

5) The expected differences in the equal noisiness contours between free-field and diffuse-field listening conditions were similar to those found by previous investigators for equal loudness contours.

REFERENCES

D. E. Bishop (1966) "Judgments of the Relative and Absolute Acceptability of Aircraft Noise," J. Acoust. Soc. Am., 40, 108.

D. E. Broadbent and D. W. Robinson (1964) "Subjective Measurements of the Relative Annoyance of Simulated Sonic Bangs and Aircraft Noise", J. Sound and Vibration, 1, 162.

R. P. Hellman and J. Zwislocki (1964), "Some Factors Affecting the Estimation of Loudness", J. Acoust. Soc. Am., 33, 687.

K. D. Kryter (1959), "Scaling Human Reactions to the Sound from Aircraft", J. Acoust. Soc. Am., 31, 1415.

K. D. Kryter and K. S. Pearsons (1963), "Some Effects of Spectral Content and Duration on Perceived Noise Level", NASA, TN D-18-B.

K. D. Kryter (1966), "Review of Research and Methods of Measuring the Loudness and Noisiness of Complex Sounds", NASA, N66-21098, April 1966.

K. S. Pearsons (1966) "The Effects of Duration and Background Noise Level on Perceived Noisiness", FAA Technical Report ADS-78.

D. W. Robinson (1964), "A Note on the Subjective Evaluation of Noise", J. Sound and Vibration, 1, 468.

D. W. Robinson and L. S. Whittle (1964), "The Loudness of Octave-Bands of Noise", Acustica, 14, 24.

D. W. Robinson, L. S. Whittle and R. M. Bowsher (1961), "The Loudness of Diffuse Sound Fields", Acustica, 11, 397.

S. S. Stevens (1955), "The Measurement of Loudness", J. Acoust. Soc. Am., 27, 815.

S. S. Stevens (1956), "Calculation of the Loudness of Complex Noise", J. Acoust. Soc. Am., 28, 807.

APPENDIX I

A. Growth of Noisiness at 1 kHz

A block diagram of the test system is shown in Figs. I-1 and I-2. The two test set-ups were used for the adjustment method and the magnitude estimation method respectively. For the first phase of the growth of noisiness tests, using the adjustment method, the pure tone test signals were generated with a BBN-designed oscillator and the noise source was an Allison Labs Model 650 noise generator. The shaping selector on the noise generator was set to deliver an equal energy per octave noise. The noise signal was sent through a Krohn-Hite Model 330 adjustable bandwidth filter set to provide the spectrum shape shown in Fig. I-3. The remainder of the system was identical for the two signals.

The signals were delivered to the Daven T-693-R attenuators and then to the BBN-designed electronic gate and Grason-Stadler Model 829E electronic switch. This gate provided the timing for the sequence of four-second samples. The start of the four-second signals was initiated by the subject's selector switch in the anechoic chamber. The gate was designed so that once a stimuli was selected it remained on for four seconds regardless of any subsequent position of the selector switch. The comparison signal channel was delivered to the electronic gate through a 100 dB ten-turn potentiometer located in the anechoic chamber. The output of the electronic switch went to a McIntosh MC60 amplifier and then to the JBL Model S-7 speaker system in the chamber. A Bruel and Kjaer Type 2203 sound level meter and Hewlett-Packard Model 130-B oscilloscope were used to monitor loudspeaker voltages during the tests. The speaker voltages were calibrated for sound pressure levels at the subject position. Measurements of stimulus sound pressure levels were made with a Bruel and Kjaer Type 4133 1/2" condenser microphone and Type 2203 sound level meter with a Type 1614 octave band filter set. A Bruel and Kjaer Type 4220 pistonphone was used to calibrate the microphone and sound level meter system.

For the magnitude estimation tests, the stimuli were recorded on an Ampex Model AG350 tape recorder and played back through the same system for the tests. The stimulus durations were four seconds with a one-second interval between the standard and comparison stimuli. A six-second
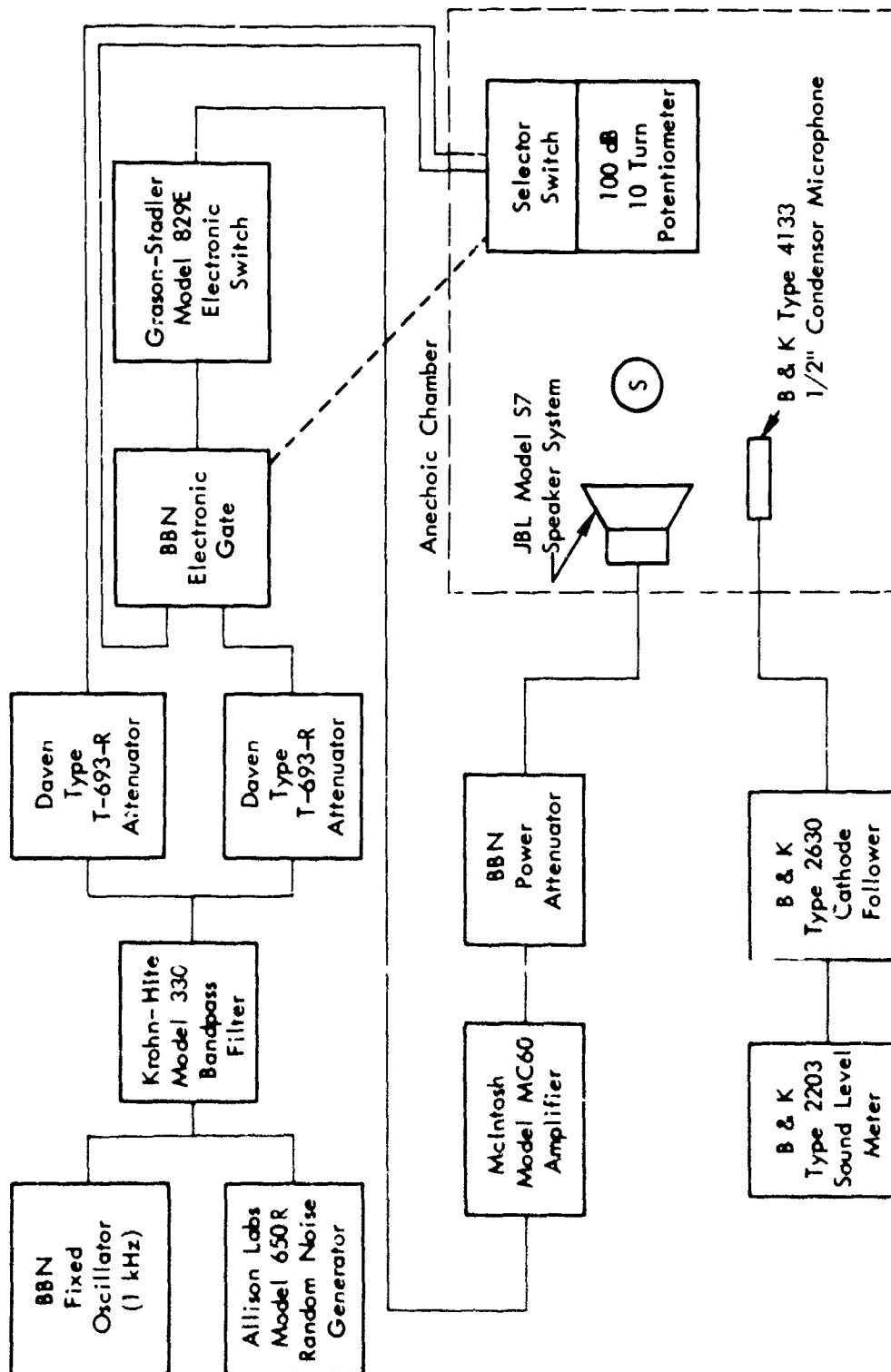
FIGURE I-I. BLOCK DIAGRAM OF EQUIPMENT USED FOR DETERMINATION OF GROWTH OF NOISINESS AT 1000 Hz USING METHOD OF ADJUSTMENT
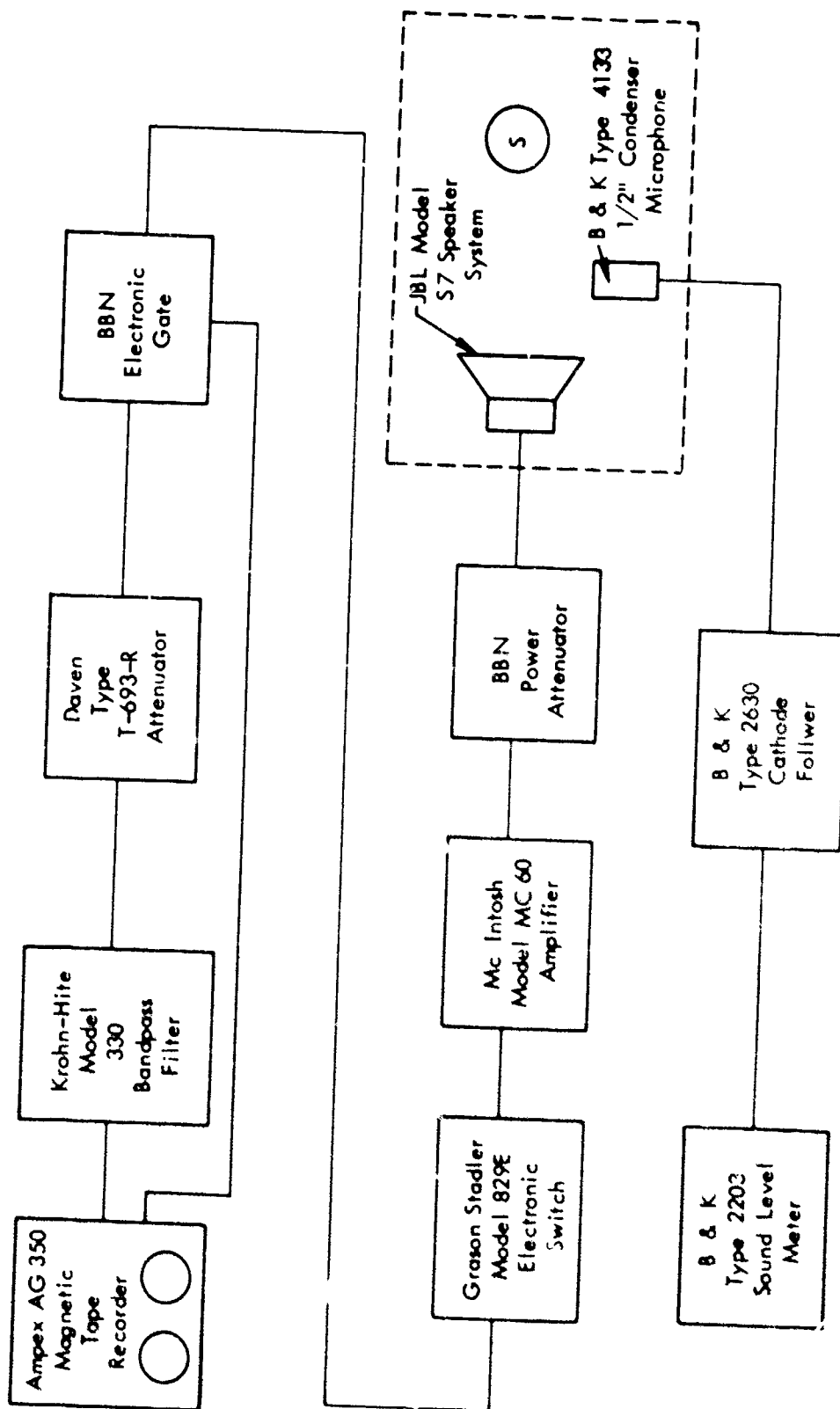
FIGURE I-2. BLOCK DIAGRAM OF EQUIPMENT USED FOR DETERMINATION OF GROWTH OF NOISINESS AT 1000 Hz USING METHOD OF MAGNITUDE ESTIMATION
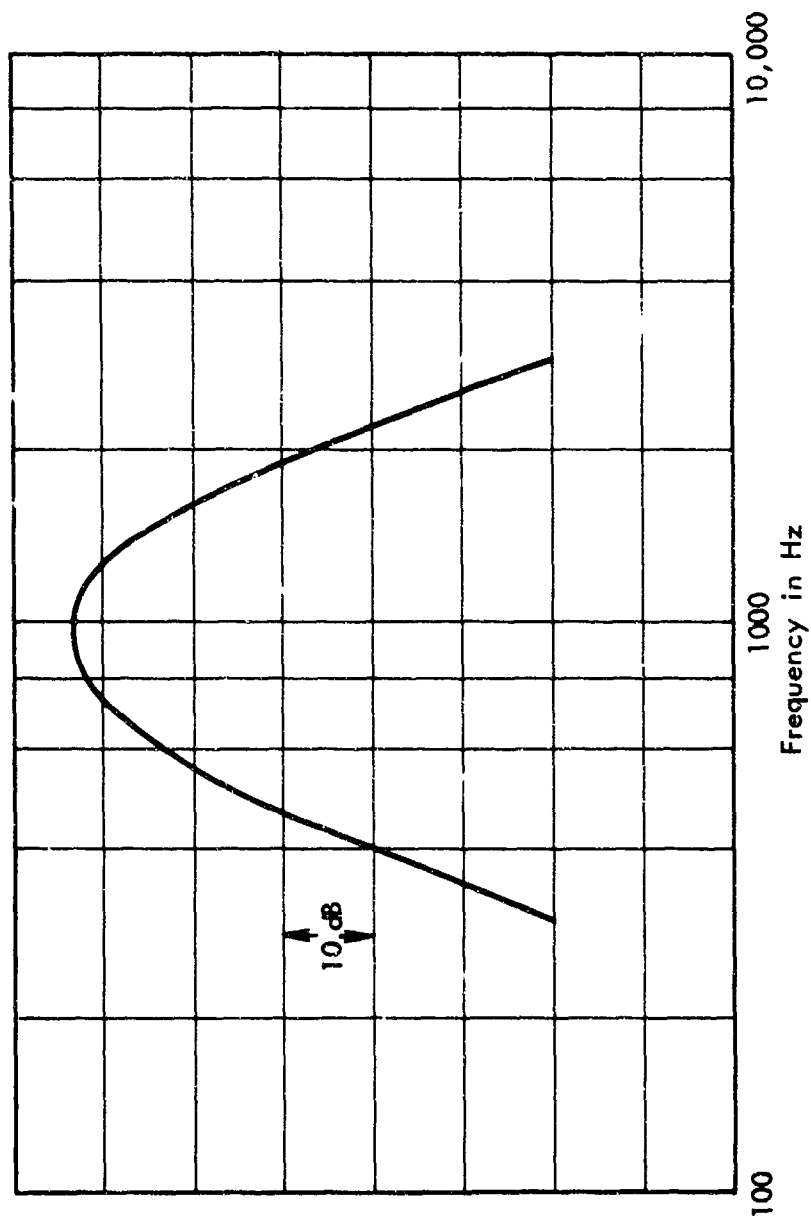
FIGURE I-3. SPECTRUM SHAPE OF OCTAVE BAND OF NOISE CENTERED
AT 1 kHz USED IN GROWTH OF NOISE

period between stimulus pairs was provided for the magnitude estimation judgments. The remainder of the test system was the same as described previously for the adjustment tests except that the gate was triggered by a pulse from Channel II of the tape recorder to reduce any audible tape noise during the tests.

All judgments were carried out in an anechoic chamber with the sound source located directly in front of the test subject. All stimulus sound pressure levels were measured at the subject position with subject removed.

B. Equal Noisiness Contours, Pure Tone Stimuli

Block diagrams of the test equipment are shown in Fig. I-4. For the pure tone tests, the BBN-designed oscillator and the Krohn-Hite Model 202R variable oscillator provided two input channels through Daven T-693-R attenuators to the BBN-designed electronic gate and Grason-Stadler Model 829E electronic switch combination. This combination performed the necessary switching and rise-decay shaping operations for the test signals. The timing of this switching operations was controlled by the Ampex Model AG350 tape recorder and polar relay system. The discrete frequency control signals were recorded on a two-channel continuous tape loop. These were played back through the AG350 system to activate the polar relay which in turn provided the switching pulses necessary for the operation of the electronic gate and the Grason-Stadler switch. The output of the comparison signal source was delivered to the electronic gate via a 100 dB, ten-turn precision potentiometer, with which the subject could adjust the levels of the comparison stimuli. The output of the electronic switch went to a JBL Model SE440S 40-watt solid state amplifier and was reproduced through a JBL Model S-7 speaker system. The loudspeaker voltages were monitored on a Bruel and Kjaer Type 2203 sound level meter, and a Hewlett-Packard Model 130-B oscilloscope. The speaker voltage was calibrated in terms of sound pressure level at the subject position.

Measurements of ambient noise levels and stimuli sound pressure levels were made with a Bruel and Kjaer Type 4133 1/2" condenser microphone and Type 2203 sound level meter with Type 1613 octave band filter set. A Bruel and Kjaer pistonphone, Type 4220, was used to calibrate the microphone and sound level meter system.

I-5
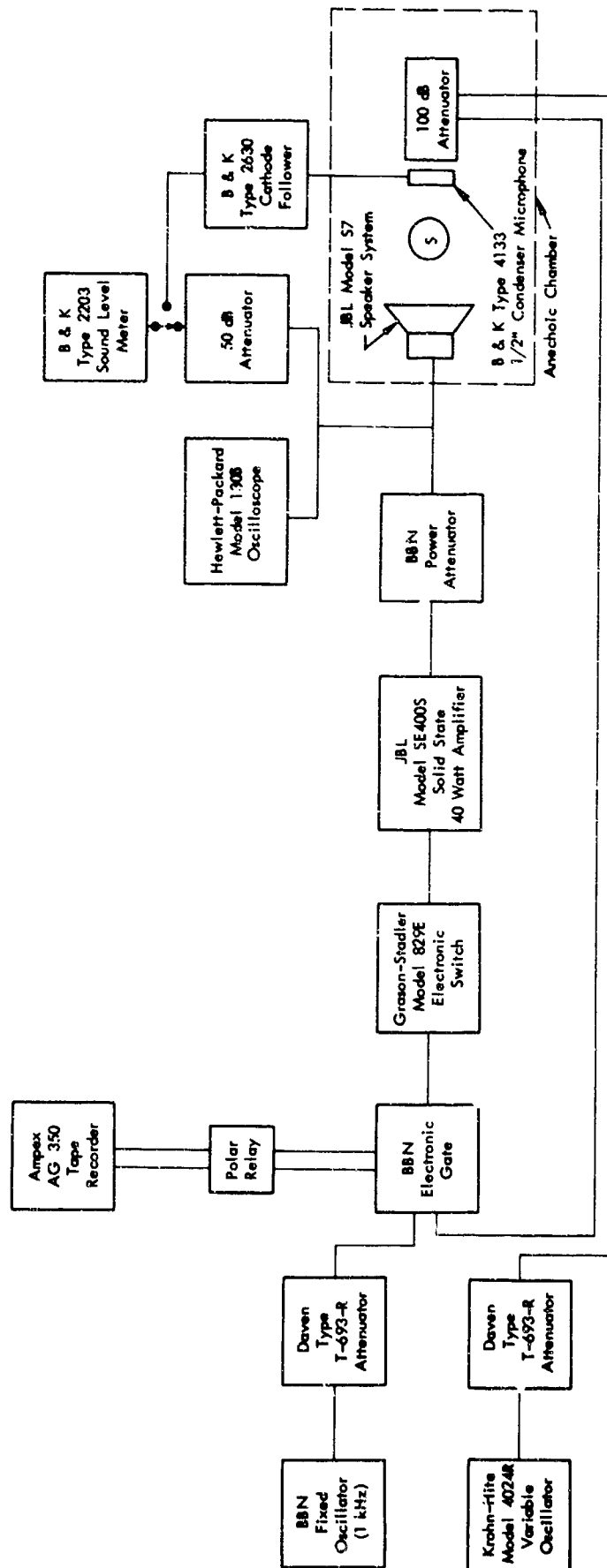
FIGURE I-4. BLOCK DIAGRAM OF EQUIPMENT USED FOR DETERMINATION OF GROWTH OF NOISINESS FOR PURE TONES AT FREQUENCIES OTHER THAN 1000 Hz

I-6

Measurements of small scale variations in sound pressure level around the subject's head position were made over an area of six inches (vertical) by eighteen inches (horizontal) centered at the average subject ear position. With no subject present, less than 1 dB variation in sound pressure level was observed over the specified area. Measurements were made at two-inch separations in both directions.

C. Equal Noise Contours, One-Third Octave Band Stimuli

The instrumentation for this series of tests was primarily the same as that used for the test series in which pure tones were used as stimuli, the difference being the spectrum of the test signal. A block diagram of the instrumentation is shown in Fig. I-5.

The source of the test signal was an Allison Labs Model 650-R random noise generator, set to produce a pink noise having equal energy per octave bandwidth. The output of the noise generator was passed through a Bruel and Kjaer Type 2603 microphone amplifier and Type 1612 one-third octave band filter set. Two outputs were available from the one-third octave band filter. One consisted of a one-third octave bandwidth signal with center frequency selectable by the experimenter. The other output was the fixed 1 kHz, one-third octave band obtained from an output on the spectrum shaper.

Two test chambers were used: An IAC anechoic chamber with dimensions 8 x 10 x 7.5 ft, and a semi-reverberant room with dimensions 14.5 x 11 x 8 ft. The test subject was seated facing the speaker system at a distance of 5 ft. A small head positioning device was included on the back of the subject chair. Measurements of ambient noise levels and stimuli sound pressure levels were made with a Bruel and Kjaer Type 4133 1/2" condenser microphone and Type 2203 sound level meter equipped with Type 1613 octave band filter set.

The semi-reverberant room was made up of four plaster walls, a cement floor and a ceiling covered with randomly perforated cellulose fiber tile. Reverberation time measurements were made in this room using an SKL Model 507 decay rate meter with the resulting values shown in Table IA.
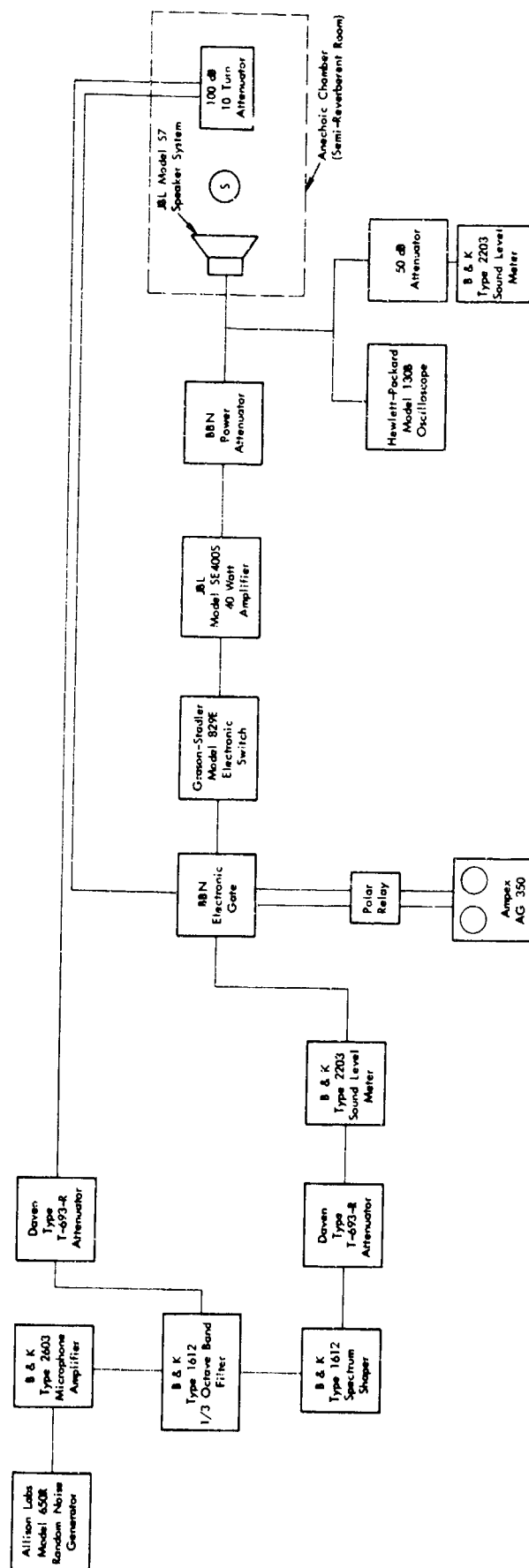
FIGURE I-5. BLOCK DIAGRAM OF EQUIPMENT USED FOR DETERMINATION OF GROWTH OF NOISINESS FOR ONE THIRD OCTAVE BANDS OF NOISE AT FREQUENCIES OTHER THAN 1000 Hz

I-8

TABLE IA

SEMI-REVERBERANT ROOM REVERBERATION
MEASURED WITH SKL MODEL 507 DECAY RATE METER

Reverberation Time in Seconds

Octave band center frequency in Hz

Room Location	63	125	250	500	1000	2000	4000	8000
Center	.99	.86	.47	.50	.50	.44	.39	
Center (Repeat Measurement)	.95	.85	.49	.49	.49	.48	.42	.39
Corner Center	.88	.88	.42	.42	.42	.42	.38	.56
Corner	.80	.83	.41	.49	.51	.39	.39	.42

APPENDIX II

APPENDIX IIA

NOISINESS OF SOUNDS
METHOD OF ADJUSTMENT INSTRUCTIONS

This test is part of a series of tests to learn more about the noisiness or unwantedness of sounds. Your task is to adjust the level of the comparison sound until its noisiness is some multiple or fraction of the noisiness of the standard sound. The particular multiple or fraction is indicated by the display in front of you.

The controls to accomplish this task consist of a "selector switch" and a "comparison level adjust control". The selector switch has three positions: "standard", "neutral", and "comparison". You may switch from the "standard" to the "comparison" as often as you wish. However, please operate the switch only during the "off" periods after a signal is presented. The level of the comparison sound can be adjusted with the comparison level adjust control. In making your judgment, we suggest that you proceed by bracketing your answer. For example, if you are asked to adjust the comparison sound until it is half as noisy as the standard, you should find levels that are greater than half as noisy and less than half as noisy before finally deciding on a level that you feel is exactly half as noisy as the standard. When you have reached your final decision, press the "finished" button and wait for a new fraction or multiple to appear in the display. Please do not change level control or switch until the new fraction or multiple appears in the display.

APPENDIX IIB

NOISINESS OF SOUNDS
MAGNITUDE ESTIMATION INSTRUCTIONS

This test is part of a series of tests to learn more about the noisiness or unwantedness of sounds. Your task is to listen to the first sound (standard) in each pair, then rate the noisiness of the second sound in comparison with the standard. In order to rate the noisiness of the second sound of each pair, you will be asked to assign one of three values to the first (standard) sound each time. These values for the standard will be 10, 100 or a value of your own choosing. The particular one of these three values you are to assign to the standard sound will be announced for each pair during the test.

You will hear a series of these pairs of sounds. Before each pair you will be asked to assign one of the three values to the first (standard) sound in the pair. After hearing both sounds in the pair, rate the noisiness of the second sound in comparison with the first. On your answer sheet write the value you would assign to the second sound based on the value you are asked to use for the standard. For example, if you are asked to use a value of 10 for the noisiness of the standard sound, and you believe the second (comparison) sound is twice as noisy as the first, you would write down a value of 20. If you believe the second sound to be half as noisy as the first, you would write down a value of 5. If you are asked to assign a value of your own choice to the first sound (standard), write down both your selection for a standard and the related value you assign to the second sound.

APPENDIX IIC

EQUAL NOISINESS INSTRUCTIONS (BBN)

This test is part of a group of tests designed to learn more about the noisiness, annoyance or unwantedness of sounds. In this particular test, you will hear two alternating tones. One of these tones has been designated the "comparison" and will be so indicated by the small light on the control box in front of you. The other tone is designated the "standard". Your task is to listen to these two alternating tones and by means of the knob in front of you adjust the "comparison" tone until it is as equally noisy or objectionable as the standard tone. It is suggested that you use a bracketing procedure; that is, adjust the comparison tone so that it is definitely less objectionable or noisy than the standard and finally adjust it to the point at which the comparison is equally as noisy as the standard tone. When you have made the adjustment for equal noisiness, push the button in front of you. Leave the control knob in the position you have decided upon during the last pair of tones until you hear a new pair of tones. Then begin the above procedure all over again.

APPENDIX IID

K-P INSTRUCTIONS FOR JUDGMENTS
OF LOUDNESS OF BANDS OF NOISE

The purpose of these tests is to determine the relative loudness of various bands of noise.

When the test starts, you will hear alternately two bands of noise presented at constant intervals. We will call the first noise the standard and the second, the comparison. The comparison noise is further identified by the panel light directly in front of you which will glow only while the comparison noise is present.

You cannot change the duration of either noise but you <u>can</u> <u>change</u> the overall intensity of the <u>comparison noise</u> by turning the knob on the attenuator that is by your right hand.

Your job is to listen to the standard noise, then to listen to the comparison noise and then to adjust the intensity of the comparison noise until it sounds as loud to you as the standard.

You may listen to the two noises as long as you wish. It is suggested that, before you proceed to equate the comparison noise to the standard noise, you make the comparison noise (No. 2) much more intense than the standard (No.1); then make the comparison noise much less intense than the standard. With those limits established, adjust the intensity of the comparison noise until it would be just as loud as the standard noise. When you have reached a decision, push the button in front of you. Leave the black knob adjusted and wait for the next trial.

K-P INSTRUCTIONS FOR JUDGMENTS
OF NOISINESS OF BANDS OF NOISE

The purpose of these tests is to determine the relative acceptability of various bands of noise.

When the test starts you will hear alternately two bands of noise presented at constant intervals. We will call the one noise the standard and the other the comparison. The comparison noise is further identified by the panel light directly in front of you which will glow while the comparison noise is present.

You cannot change the duration of either noise but you can change the overall intensity of the comparison noise by turning the knob on the attenuator that is by your right hand.

Your job is to listen to the standard noise, then to listen to the comparison noise and then to adjust the intensity of the comparison noise until it sounds as acceptable to you as the standard. By equally acceptable we mean that you would just as soon have one as the other in or outside your home periodically 20 to 30 times during the day and night. Stated another way, we mean by equally acceptable that the comparison noise would be no more nor no less disturbing to you in or outside your home than the standard noise.

You may listen to the two noises as long as you wish. It is suggested that, before you proceed to equate the comparison noise to the standard noise, you make the comparison noise much more intense than the standard; then make the comparison noise much less intense than the standard. With those limits established, adjust the intensity of the comparison noise until it would be just as acceptable as the standard noise in or outside your home. Please push the button on your right to indicate that you have reached a decision.

APPENDIX III

by

David M. Green
Dwight E. Bishop
John E. Parnell

EXPONENT IN THE POWER LAW AND
LOUDNESS OR NOISINESS CALCULATION

The calculation of loudness level as proposed by Stevens (1956), and the adaptation of this proposal for the calculation of the perceived noise level as described by Kryter (1959), involves four separate parts. (1) There is a set of standard contours called equal loudness or noisiness contours relating the sound pressure level in different frequency bands needed to achieve the same loudness or noisiness. (2) There is a growth function relating sound pressure levels of a standard sound (1000 Hz) to an internal scale whose unit is the sone in the calculation of loudness and the noy in the calculation of noisiness. (3) There is a rule for combining the loudness or noisiness in different frequency bands into a total quantity representing the overall loudness or noisiness of the sound. (4) Finally, there is conversion of this total quantity back to the sound pressure level of some standard stimulus such as a 1000 Hz sinusoid in the case of loudness, or a standard band of noise in the case of noisiness. This last step is simply the inverse of the growth law assumed in Step (2) above.

Since the only difference between the procedures for calculating noisiness and loudness is the set of standard contours, we can illustrate the major point of this appendix by reference to the calculation of noisiness and omit reference to the loudness calculation. This will simplify the exposition, but the reader should remember that the conclusions apply equally to the calculation of loudness or noisiness.

The large degree of independence between the final calculated value and the exponent of the power law results because of the highly non-linear procedure (picking a maximum) used in determining the total noisiness from the noisiness of the individual bands (Step 3), and the fact that Step (4) and Step (2) are inverses of one another.

Calculations

In the calculation procedure, a steady-state sound is analyzed by measuring the rms pressure in successive octave or third-octave bands. We shall consider only octave band analysis but the general conclusions will pertain to third-octave analyses as well. Let us denote by p_i the rms pressure measured in the ith octave band.

Each p_i is converted to a noisiness n_i via the following equation:

$$n_i = \left(\frac{p_i}{k_i}\right)^{\alpha} \quad i = 1, 2 \ldots 8 \tag{1}$$

where k_i is a constant and α is the exponent of the power law. The set of numbers $k_1, k_2 \ldots k_8$ define the equal noisiness contours. Actually, the equal-noisiness contours are not exactly parallel (α may depend slightly on the frequency band and level) but this detail need not concern us in the present matter.

This rule for determining the total noisiness n_t involves picking the largest noy value, n_{max}, and adding that value to the weighted remainder.

$$n_t = n_{max} + F \ \Sigma \ (n_i - n_{max}) \tag{2a}$$

or letting

$$\Sigma \ (n_i - n_{max}) = \mathop{\Sigma}_{i \neq max} \ n_i$$

then

$$n_t = n_{max} + F \mathop{\Sigma}_{i \neq max} \ n_i \tag{2b}$$

where F is a constant, ($F = 0.3$ in current procedures for octave bands).

We can also write the calculation of n_t as a function of the pressure in various band, using Eq. 1 and 2b,

$$n_t = \left[\left(\frac{p}{k}\right)_{max}\right]^{\alpha} + F \mathop{\Sigma}_{i \neq max} \left(\frac{p_i}{k_i}\right)^{\alpha} \tag{3}$$

Finally, we note that the perceived noise level in PNdB, PNL, is defined as follows:

$$PNL = 20 \ \log \ (n_t)^{\frac{1}{\alpha}} + C \tag{4}$$

III-2

where C is a constant, the PNL corresponding to 1 noy. The value of α is 0.6 and C is 40 dB in the current calculation procedure.

Clearly if the sound is a pure tone, there will be only one noisiness value, and since Eq. 1 and Eq. 4 find the α-power and α-root of the same quantity, the PNL is essentially the pressure level of the pure tone re the pressure corresponding to 1 noy for that band. Thus, for a pure tone, the value of the power law exponent, α, has no effect whatsoever.

To provide an idea of how little the particular exponent of the power law effects practical calculations, six hypothetical sound spectra encompassing a variety of spectrum shapes were selected for noisiness calculations with different growth functions. The six spectra are shown in Fig. 1. The spectra shown are adjusted in level to yield the same calculated perceived noise level, 106 PNdB (97 noys) by current noisiness calculation procedures (K. D. Kryter and K. S. Pearsons, 1963 and 1964) (Within a total spread of 0.5 PNdB). Then we changed the power law exponent, α, by multiplying it by m, where m = 3, 2, 1, 1/2, 1/3. From Eq. 4, it can be seen that this changes the number of dB the perceived noise level changes for a doubling of the total noisiness; for example, 3 dB if m = 3, 5 dB if m = 2, 10 dB if m = 1 (the present exponent), 20 dB is m = 1/2, and 30 dB if m = 1/3.

In making these calculations, separate values of the constant F were assumed for each of the assumed growth functions. (Note that changing F essentially changes the weight given the noisiest frequency band with respect to the noisiness contributed by the remaining octave bands).

The value of F was chosen via Eq. 2b. For each spectrum, n_{max} and $\sum_{i \neq max} n_1$ are known as well as the desired value for n_t, thus, F could be determined. The approximate median values so obtained were F = 6.6, 1.4, 0.3, 0.09, 0.05 for m = 3, 2, 1, 1/2 and 1/3 respectively. With these values of F_1, n_t was calculated for each of the six spectra.

In comparison with the original spread in perceived noise levels of 0.5 PNdB for the current growth law of 10 dB per doubling of noisiness, the spread ranged from 0.5 to 2.8 PNdB for the changes of 3 to 30 dB per doubling of noisiness. This range must be considered small when it is realized that the actual change in the spectra as a function of frequency is about 40 dB, in addition to the large change in assumed growth law.

Discussion

Implications that one draws from this analysis depend in large part on the motives one has for using these calculation procedures. The observation that the calculation of the perceived noise or the loudness level is largely unaffected by the value of the exponent of the power law in no way challenges the claim that raising the sound pressure level by 10 dB doubles the noisiness or loudness. That rule is the power law and this appendix in no way challenges that relationship. In practical application of noisiness or loudness calculation, however, two sounds are often compared and one wants to know if they differ in perceived noise level by 2 PNdB, 7 PNdB, or 20 PNdB. Similarly, the effects of sound treatment are seldom expressed numercially as reduction of noisiness but rather that the treatments caused a 5 PNdB reduction in the perceived noise level. The latter numbers are not much affected by the form of the growth law.

Such invariance is a virtue because there may be differences among subjects as to the exact form of the growth law (W. J. McGill, 1960; J. C. Stevens and M. Guirao, 1964). Despite these differences, people may still agree that two sounds are different by about the same number of decibels. It also suggests that, since one exponent has much the same effect as any other, convenience might well dictate the choice of the exponent in a loudness or noisiness meter.
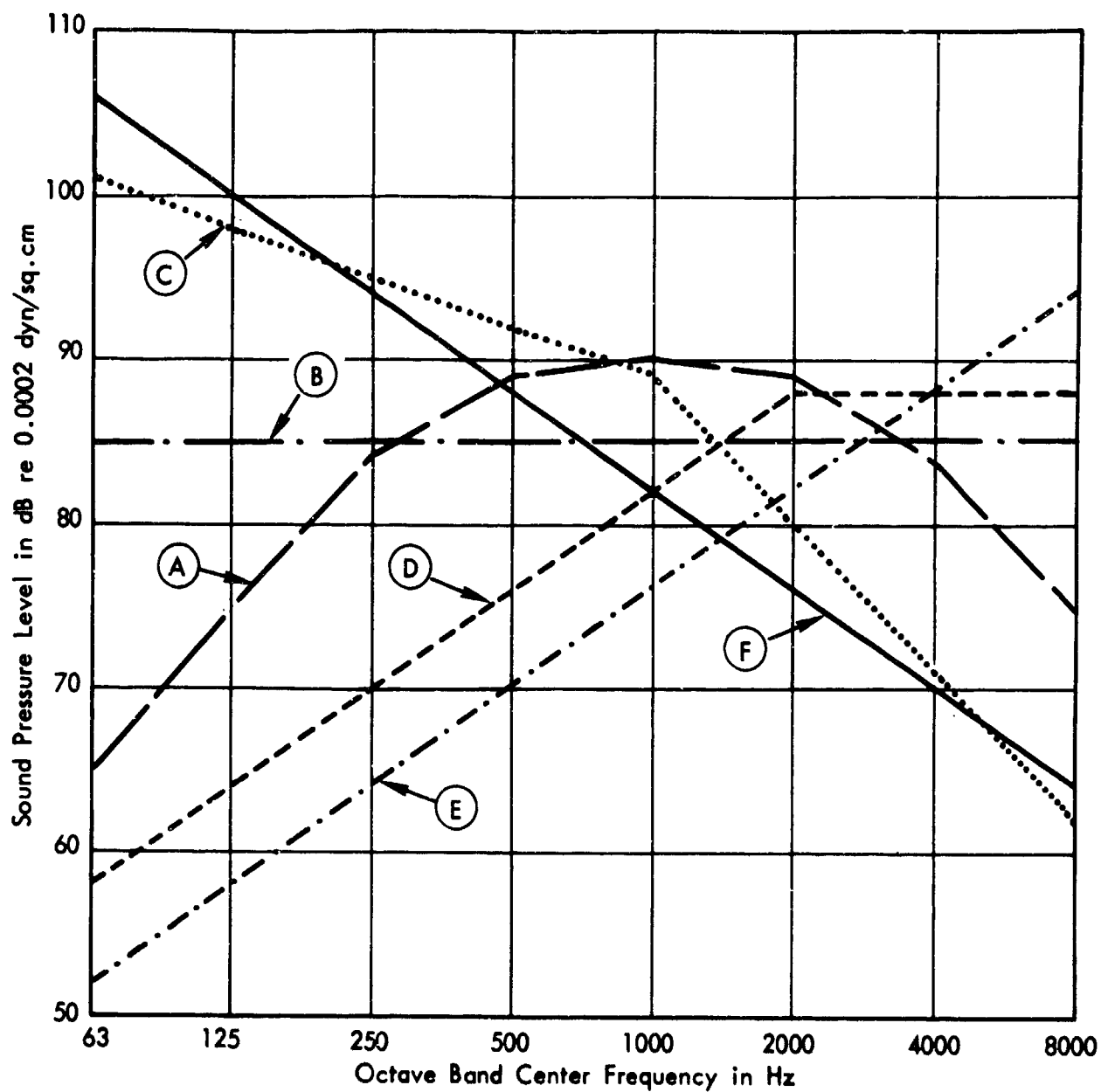
FIGURE III-1. NOISE SPECTRA EMPLOYED IN GROWTH OF NOISINESS
CALCULATIONS

REFERENCES

1. Kryter, K. D. (1959), *J. Acoust. Soc. Am.*, 35, 1415-1429.

2. Kryter, K. D. and Pearsons, K. S. (1963), *J. Acoust. Soc. Am.*, 35, 866-883, and Kryter, K. D. and Pearsons, K. S. (1964), *J. Acoust. Soc. Am.*, 36, 394-397.

3. McGill, W. J. (1960), "Psychological Scaling: Theory and Application", (John Wiley and Sons, New York), H. Gullichsen and S. Messick (Eds), Chapter 7, 67-81.

4. Stevens, J. C. and Guirao, M. (1964), "Individual Loudness Functions", *J. Acoust. Soc. Am.*, 36, 2210-2213.

5. Stevens, S. S. (1956), *J. Acoust. Soc. Am.*, 28, 807-829.